DEPARTMENT OF THE INTERIOR—U. S. GEOLOGICAL SURVEY

J. W. POWELL DIRECTOR

THE

MECHANICS OF APPALACHIAN STRUCTURE

BY

BAILEY WILLIS

EXTRACT FROM THE THIRTEENTH ANNUAL REPORT OF THE DIRECTOR, 1891-'92

WASHINGTON
GOVERNMENT PRINTING OFFICE
1894

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CONTENTS.

ILLUSTRATIONS.

THE MECHANICS OF APPALACHIAN STRUCTURE.

By Bailey Willis.[1]

INTRODUCTION.

The facts of the following discussion are drawn from the belt of disturbed Paleozoic strata which extends from New York, through Pennsylvania, the Virginias, and Tennessee, to Georgia and Alabama.

This is an area of about 60,000 square miles—900 long and 50 to 125 miles wide. It is a geologic province distinguished by the age of its strata from the region on the east and by the facts of its structure from the horizontal rocks on the west. Toward the east extend crystalline rocks much older than the Paleozoic and part of that continent which yielded the materials for Paleozoic sediments. On the west is the area over which the mediterranean sea of North America prevailed during the periods from Cambrian to Carboniferous. Between the continental edge and the open sea was the narrow belt where mechanical and organic sediments accumulated in great bulk. This strip is the zone of strongly developed structural deformation.

The phase of deformation is that which follows from compression. Across this zone the arc once covered by the strata has shortened and the greater length of the beds has been taken up by folding and faulting. The folds and faults formed on a vast scale, with simple relations among themselves, and conditions of erosion have led to the development of a relief in close accordance with the occurrence of hard and soft rocks. Hence it follows that the general character of structure in this region is easily recognized, and through the great work of H. D. Rogers, followed by W. B. Rogers, Lesley, Safford, and many others, it has become widely known as a definite type. The term "Appalachian structure" conveys in geologic literature the idea of strata compressed into long narrow folds, generally parallel among themselves, and sometimes overturned, and overthrust.

This is a simple conception which recognizes a generic result due to a single cause and which disregards specific differences due to varied conditions. But such differences exist among the folds and faults and divide them into distinct types, sometimes intimately associated, some-

[1] To Mr. G. K. Gilbert and to my associates in the Appalachian province. Messrs. Hayes, Keith, and Campbell, I am indebted for many facts and for frank discussions of hypotheses, which have greatly aided in the preparation of this paper.—B. W.

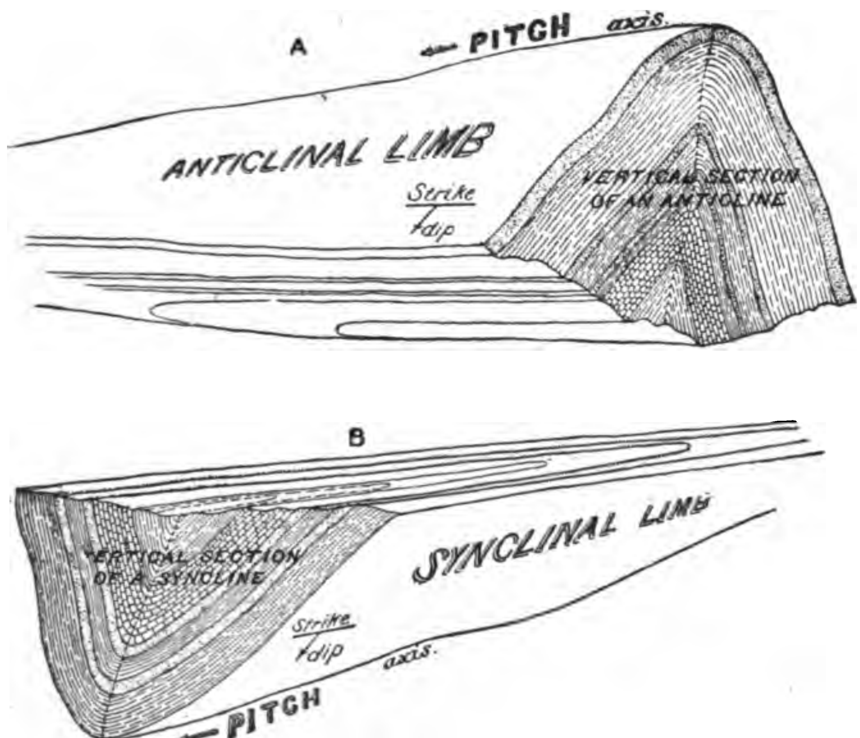
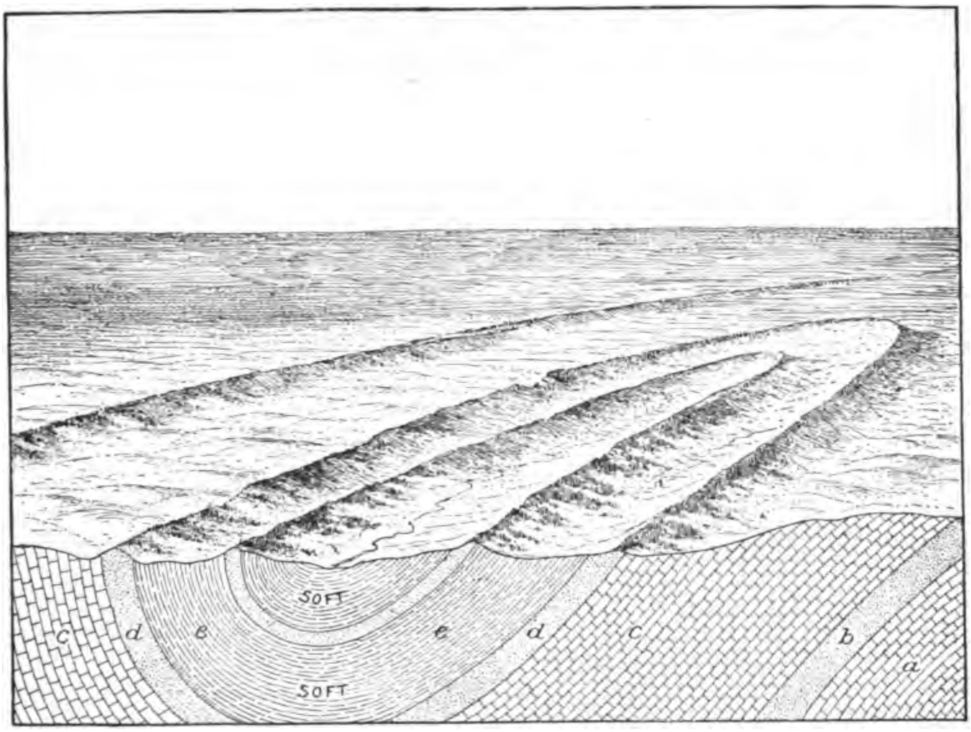
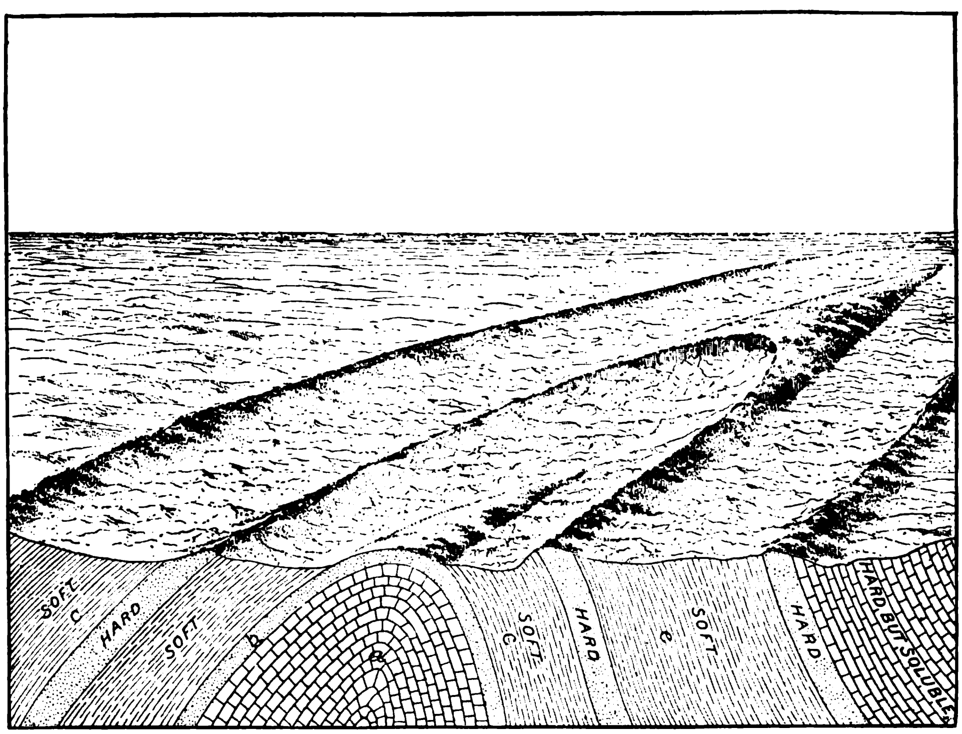


FIG. 16. Parts of folds.



SYNCLINE.

Perspective view and vertical section, showing the spoon-shaped ridges of hard rock and the troughs formed by the beds.



ANTICLINE.

Perspective view and vertical section, showing the half-cigar-shaped mountains of the hard rocks and the arches formed by the beds.

times independently developed, and occurring with conditions of stratigraphy to which they may be causally related. The steps which lead logically to a conception of these possible relations are:

(1) Description of the types of structure.

(2) Statement of their relations, geographic, as among themselves, and stratigraphic—that is to the series of strata deformed.

(3) Experiments to reproduce structures.

(4) Discussion of the laws developed by experimental study and their application to natural phenomena.

TYPES OF STRUCTURE.

Strata are deposited in a nearly horizontal position, and in the case of continuous deposition successive beds are essentially parallel. Under compressive force the beds may change their attitude to one of greater or less inclination, while remaining nearly parallel among themselves. This is flexure, or folding. Or the force may cause such changes in their relative attitudes as to destroy their parallelism and change the order of superposition. This is faulting.

FOLDS.

The two great types of folds are the syncline and the anticline.

The syncline (pli synclinal, fond de bateau, auge, mait, V ou pli en V; synclinal-Falte, Mulde). This is the simplest type; it is a depression of the the strata from a flat to a basin-shaped form. In cross section it may be shallow and gently rounded, or vary to a deep, straight-sided, and sharply angular trough. In plan view it is, in the Appalachians, usually very long and acute at the ends; hence the use of the adjective "canoe-shaped." Geometrically, a syncline is characterized by the fact that it is concave upward. Geologically, it is determined by the presence of younger strata within the basins of the older.

The anticline (pli anticlinal, voûte, soulèvement en voûte, selle; Gewölbe, Sattel). The companion type of the syncline is the anticline, or arch; this is an elevation of the strata in a direction opposed to gravity, from a flat to a dome-like or semi-cigar-shaped form. The cross section varies from a broad, gentle arch to an acute straight sided roof. In plan the fold is usually very long and narrow. Geometrically, the anticline is recognized by its upward convex curve; geologically, it is distinguished by the presence of older strata within the domes of the younger.

PARTS OF FOLDS.

Any syncline or anticline consists of two sides, which meet along a line of lowest depression or of greatest elevation. The sides may be called the limbs, slopes, flanks, branches, legs, or shanks (les flancs, ailes, jambages, combles, montants, pans, reins, pendages; die Schenkel, Flügel).

The line or area of meeting of the sides is the axial region, the crest or crown of an anticline, the base or bottom of a syncline (charnière anticlinale, sommet, tête, clef de voûte; Gewölbebiegung; charnière synclinale, fond; Muldenbiegung).

The angle included between the limbs of any fold may be bisected by a plane; such a plane is the axial plane and the line by which it intersects the stratum is the axis of the fold. Folds include many strata, each of which has its axial plane and axis; if the fold be regular the bisecting planes may coincide, but in irregular folds they will form parts of a warped surface. Instead of axial plane we may then speak of axial surface and define it as the surface whose elements are the axes of all the strata involved in the fold. To define the attitude of the side of a fold it is usual to give the strike and dip of a stratum of the fold; that is, the azimuth of a level line drawn on the stratum and the angle between a line drawn at right angles to this and a horizontal plane. In the same way the position of a fold can be defined by giving the azimuth or strike of its axis and the angle made by the axis with a horizontal plane; the latter may be called the pitch of the axis to distinguish it from the dip of either side.

COMBINATIONS OF FOLDS.

Anticlines and synclines seldom occur as separate individuals; they are usually combined, lying side by side in alternation, uniting by convergence of several axes to form one, or dying out by the merging of the pitch of an axis with the dip of a stratum. It often happens that the result of the combination of many anticlines and synclines is to form a complex structure, which, regarded as a whole, is either synclinal or anticlinal. The former is called a synclinorium, the latter an anticlinorium.

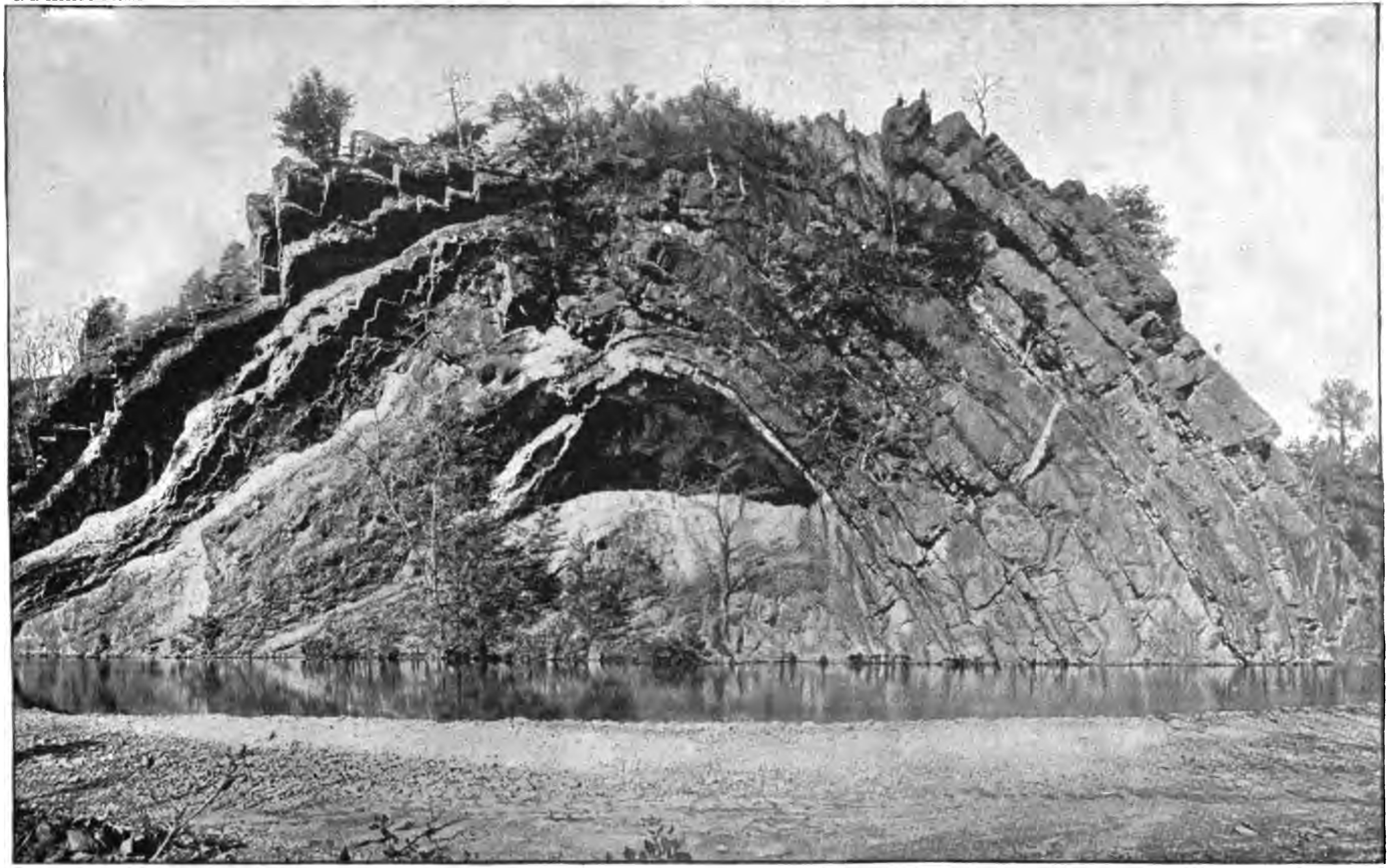
VARIETIES OF FOLDS.

Folds have been classified in two ways: First, by the relative amount of opposed dips; second, by the degree of compression which they have suffered.

According to the first classification we have:

Upright or symmetrical (droit; Normalgestellt, stehend, aufrecht stehend, gleichformig), when the opposed dips are the same; the axial plane is then vertical.

Unsymmetrical (oblique, dejeté, pli en genou; Schief, geneigt, stehend ungleichformig), when one dip is steeper than the other; the axial plane is then inclined. When one limb is inclined beyond the perpendicular the unsymmetrical fold is called: Overturned, inverted, collapsed, overthrown, reflexed fold, sigma flexure, sigmaflex, sigmoidal flexure (pli renversé, repli; ueberliegende Falte, überhangende Falte).



ANTICLINE IN SILURIAN STRATA ON THE POTOMAC RIVER, NEAR HANCOCK, MARYLAND.

Recumbent fold (pli couché; liegende Falte, liegendes Gewölbe), when the inverted dip approaches horizontality.

In the inverted and recumbent folds it is important to distinguish between the three limbs of the anticline and its subjacent syncline, because when a fold has progressed to that condition of overturning, the influence of the thrust in developing structure in the several limbs is different according to their situation. We may therefore designate the upper limb of the anticline as the arch limb or roof (flanc normal supérieur, flanc normal de l'anticlinal; Gewölbeschenkel, Dach, oberer aufrechter Schenkel); the middle limb between the anticline and syncline as the common limb, partition, or reverse limb (flanc médian, flanc renversé; Mittelschenkel, verkehrter Schenkel); and the lower limb of the syncline as the trough limb, or floor (flanc normal inférieur, flanc normal du synclinal; Muldenschenkel, unterer aufrechter Schenkel). We may also speak of the turn at the top of the anticline, and of that at the base of the syncline as the upper and lower bends (charnière supérieure et charnière inférieure; obere Umbiegung und untere Umbiegung).

These designations are appropriate when we regard the overturned anticline and its subjacent syncline as forming a single structure, which, in so far as dynamic results are concerned, they may often be said to do.[1]

According to the second classification we have:

Open folds. When the limbs of an anticline or a syncline are wide open respectively downward or upward further shortening of the zone of strata is possible by the lessening of this angle; such may be called open folds.

Closed folds. When this angle can not become more acute without the squeezing of the strata the fold may be said to be closed.

Carinate or isoclinal folds. Under certain conditions the limbs of a fold, whether anticlinal or synclinal, may become parallel, the uppermost or undermost bed of the folded series being bent back upon itself so that its upper or lower surface is like a sheet of paper folded in a single crease. The strata are then repeated on either side of the axis, but they show a uniform dip. The single anticline or syncline of this type has a keel and may be called carinate; repeated folds with parallel limbs are termed isoclinal (pli isoclinal; Isoclinalfalte).

Isoclinal folds may present perpendicular or overturned dips, or may in some cases be almost horizontal; they are accordingly called upright, overturned, or recumbent isoclinal folds (pli isoclinal droit, pli isoclinal renversé, pli isoclinal couché; aufrechte Isoklinalfalte, überkippte Isoklinalfalte, schiefe Isoklinalfalte, liegende Isoklinalfalte).

A further development of the isocline is produced when the compression, coming at right angles to the buried vertical strata, so narrows the deeper part of the anticline or the higher part of the syncline as to produce respectively an angle open upward or one open down-

[1]Secret of the Highlands. Chas. Lapworth, F. G. S., Geol. Mag. II, vol. x, 1883.

ward, the reverse of the ordinary condition of anticlinal or synclinal folds. Such folds are called fan-shaped (pli en éventail; Fächerfalte). They represent the extreme phase of folding and their occurrence is limited to those parts of mountain masses which have been subjected to most extreme compression, and probably at very considerable depth in the earth's crust. French and German geologists have further classified fan-shaped folds as upright, as overturned, or as recumbent, according to the relation of the dips to the vertical or horizontal plane.

Fan-shaped folds contradict the geometrical definitions of synclinal or anticlinal structures; their character is therefore to be determined only by the relation of younger to older strata. If they are synclines the younger strata are within and if anticlines they are outside of the older strata.

FAULTS.

A fault is that result of deformation which destroys the regular order of superposition of strata. It is not to be confounded with an unconformity, which implies an interval of erosion between an older and a younger series. To avoid confusion of terms we may use them as follows:

Fault: To designate the relation of strata not continuous or parallel because they have been forced the one series past or over the other.

Unconformity: To designate the relation of strata not parallel because the older series was upturned, eroded, and submerged before the deposition of the younger upon the eroded surface; this is an unconformity by dip and erosion. The term also applies to cases where the strata of two periods are parallel but are in contact over an eroded surface of the older; this is an unconformity by erosion.

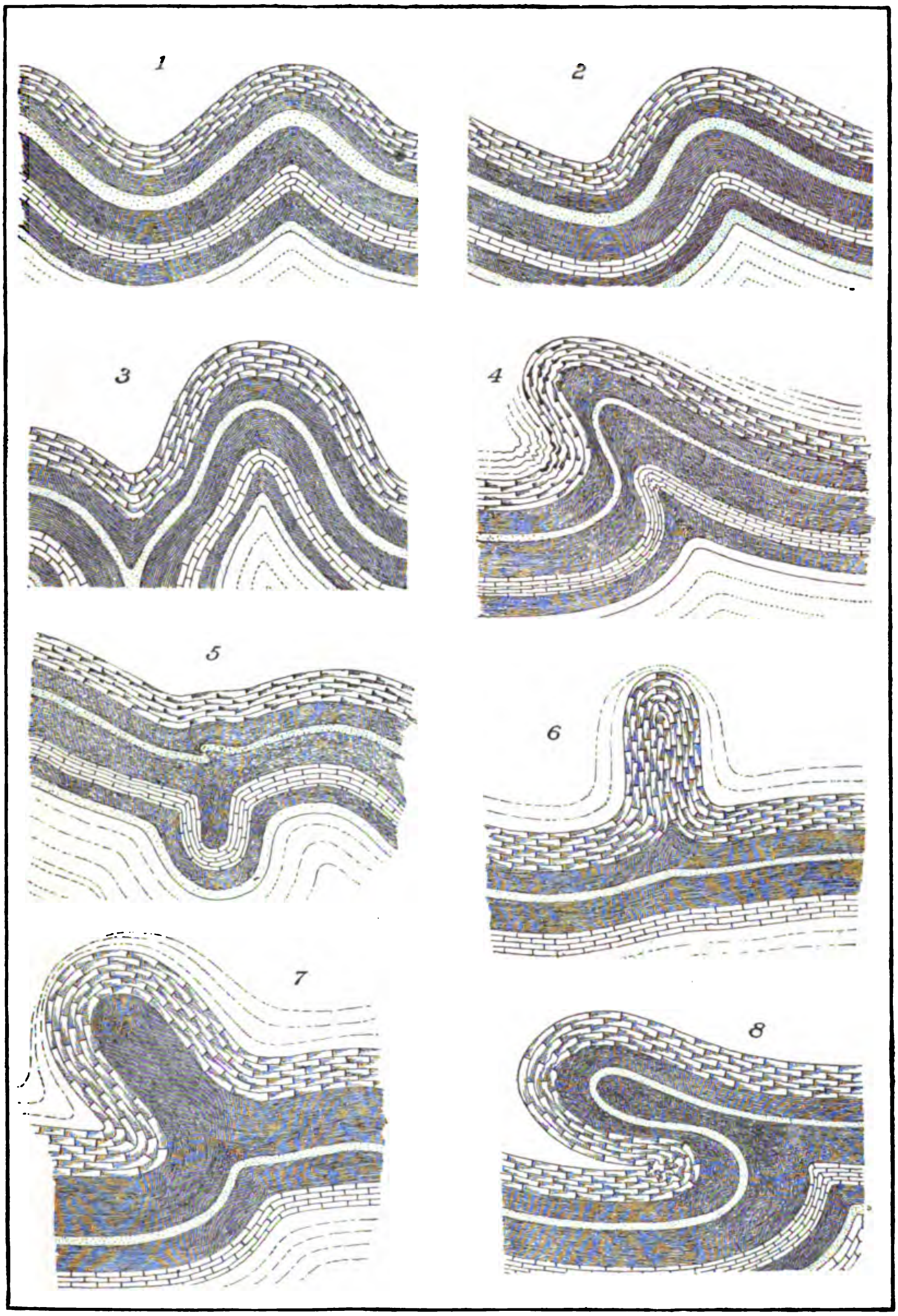
Discordance: To designate the relation of strata not parallel in cases where the process resulting in absence of parallelism is in doubt.

CLASSIFICATION OF FAULTS.

The term fault is of general application to any dislocation of rocks involving movement of the separated masses past one another, and it therefore covers what has been called the normal or radial fault, which is a phase of deformation involving extension of an arc of the earth's crust. This type is precisely the opposite of the dislocation which arises from compression and which has been called reversed fault, compression fault, or thrust fault. Long usage has so identified the word fault with what is called the normal type, that clearness and precision are gained by employing a substitute for it in describing dislocations due to compression, and for this purpose there is none better than *thrust.*

Thrusts may arise from any one of four sets of conditions, and if classified genetically may be called—

First. The shear-thrust; this arises when either force or resistance is so concentrated as to produce a plane of easiest motion, along which



TYPES OF FOLDS.

1. Symmetrical or upright fold, open.
2. Unsymmetrical or inclined fold, open.
3. Symmetrical or upright fold, closed.
4. Unsymmetrical fold, closed and overturned.
5. Syncline showing a keel: a carinate syncline.
6. Carinate anticline, the lower strata remaining flat.
7. Carinate anticline, overturned.
8. Carinate anticline, recumbent; or recumbent fold.

shearing meets with a resistance less than that opposed by the strata to bending. The Scotch geologists first described this type, and it is illustrated by a figure from the article on the northwest Highlands.[1] (Pl. LIII.)

Second. The break-thrust; this develops when strata form first an anticline, so conditioned that in process of development folding soon becomes more difficult than breaking, followed by overthrust on the fracture plane. This is the characteristic type of faulting in the Appalachian province, and it is illustrated by drawings based on the interpretation of observed facts. (Pl. LIII.)

Third. The stretch-thrust; this is the result of extreme folding, with development of an overturned limb, which is stretched by the opposite pressures of the roof and floor. This type has been described by Heim, and is illustrated by diagrams from Mechanismus der Gebirgsbildung. (Pl. LIII.)

The shear-thrust is independent of flexure; the break-thrust follows moderate folding; the stretch-thrust is a final phase of a closed and overturned fold.

Fourth. The erosion-thrust; this may develop when a rigid stratum rises from a broad syncline to outcrop on an eroded anticline. Then, if compression follows, the stratum meets with no resistance and rides forward over the subaerial surface. Such a thrust, complicated indeed by a break-thrust, is shown by Hayes,[2] and a simpler form is suggested in Pl. LIII. The difference between the two illustrations lies mainly in the relative ages of the strata brought into contact.

PARTS OF FAULTS.

A fault is a surface of two dimensions only, the surface of movement between two masses of strata. This surface has length and width; it may be accompanied by phenomena of schistosity or crushing which occur to some slight distance on either side of it, and, if these be considered with the plane of movement, there is a thickness, but it is very minute as compared with the other dimensions.

The length of a fault is the length of its outcrop between the extremes where it fades out or passes into a fold. This is measurable by miles, and may reach to hundreds of miles.

The width of a fault may be stated as the distance from the outcrop to its subterranean limit; such a limit is always a matter of inference, and the width is only conjecturally measurable.

The amount of movement on a fault plane is expressed by important measures. These are:

Displacement: The distance measured on the fault surface between the repeated ends of one stratum.

[1] Recent work of the Geological Survey in the Northwest Highlands of Scotland, A. Geikie, Quart. Journ. Geol. Soc. for August, 1888.

[2] The Overthrust Faults of the Southern Appalachians. Bull. G. S. A., Vol. 2, pp. 141-154.

Vertical throw: The vertical height of one end of a stratum above that from which it has been disconnected, both at the fault surface. This is also called, simply, throw.

Horizontal throw: The horizontal distance by which one end of a stratum has been pushed beyond the other; this is also called heave.

Stratigraphic throw: The thickness of strata belonging in orderly sequence between the strata faulted into contact.

Fault dip: The angle between the fault surface and a horizontal plane. This is the complement of the "hade," a term originally applied to normal faults and one which may well be restricted to that class of displacements.

STRUCTURAL DISTRICTS OF THE APPALACHIAN PROVINCE.

In the Appalachian province there are four districts, each of which is distinguished from the others by a prevailing structural type. These districts are as follows:

(1) District of open folding: Alleghany region of Pennsylvania and West Virginia.

(2) District of close folding: Appalachian valley.

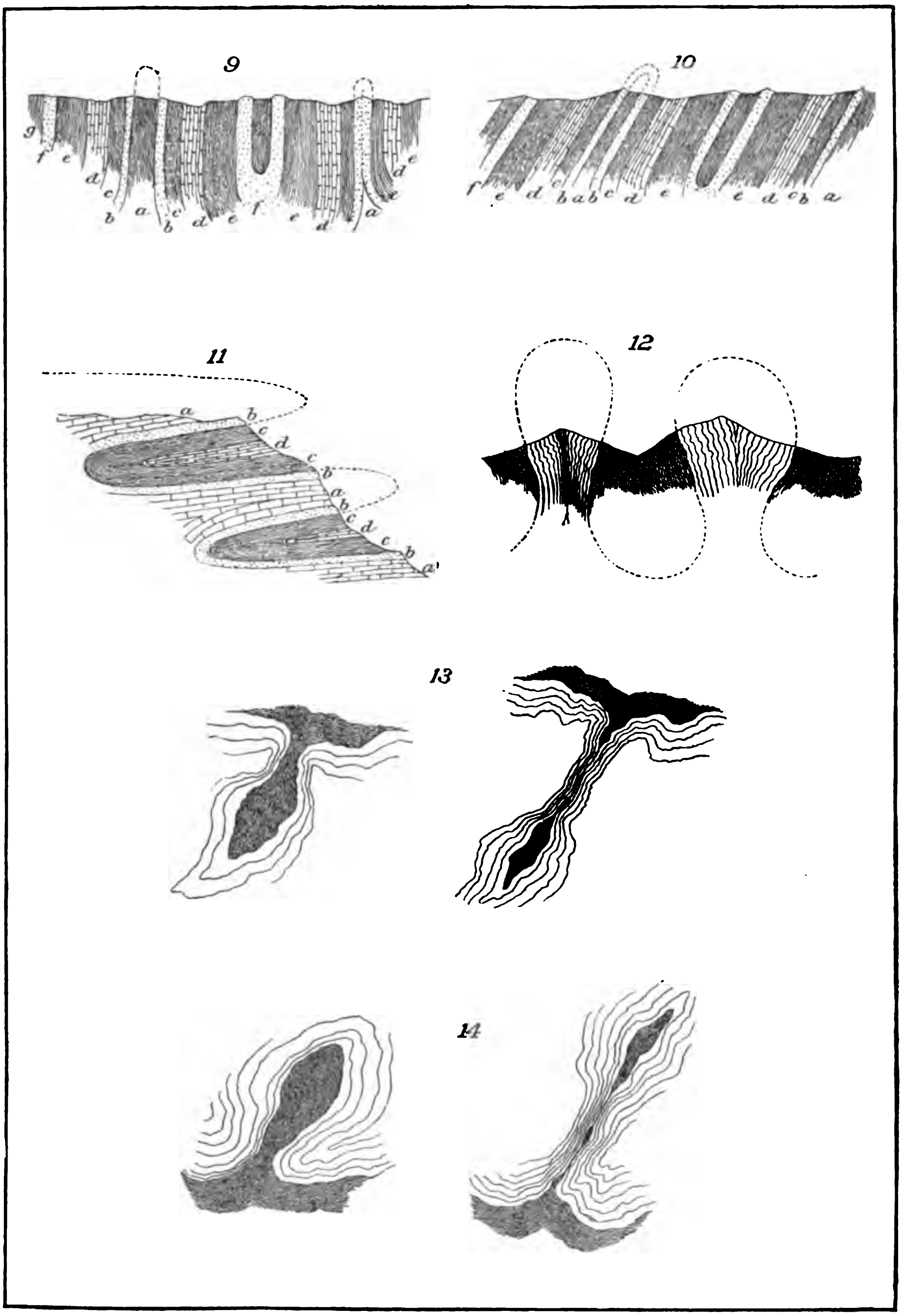
(3) District of folding and faulting: southern Appalachian region of Virginia, Tennessee, and Georgia.

(4) District of folding with schistosity: Smoky mountain region.

Each of these districts, with its typical structure, is described in the following pages:

DISTRICT OF OPEN FOLDING—PENNSYLVANIA-WEST VIRGINIA.

From the pleateau region of southern New York through Pennsylvania to the southern part of West Virginia extends an area of simple geological structure characterized by the development of open folds. On the eastern side its limiting ridges command the Appalachian valley and on the west it is in turn overlooked by the escarpment of the Alleghany front. Deep, closed folds do occur in the anthracite basins within this area and faults are occasionally present, but they are short and of moderate displacement. The dominant type is the open anticline, tens of miles long, single miles wide, not straight, but sweeping in gentle curves with the trend of the belt. In general relations parallel, they yet diverge to inclose a broader syncline than usual, or sink and fade into a deeper one. Some arches are much larger than their fellows, and are thus conspicuous; again, individual features of groups exhibit wave-like parallelism and equality. The dips are more often over than under 45°, frequently steeper northwest than southeast, and sometimes the strata are vertical, but the general result of deformation is irregular undulation of the strata.



TYPES OF FOLDS.

9. Repeated carinate or "isoclinal" folds, upright.
10. Isoclinal folds, inclined.
11. Isoclinal folds, recumbent.
12. Fan-structure, upright.
13. Squeezed syncline and detached synclinal core.
14 Squeezed anticline and detached anticlinal core.

After Heim and Margerie.

Rogers stated, and the statement has long been accepted, that the waves of strata exhibit their greatest development in the east and gradually die away toward the northwest. The idea conveyed is that the force causing deformation acted most energetically in producing the eastern folds, and became less and less effective as it proceeded farther from its source. If this were true, the greater folds should lie toward the eastern edge, the lesser toward the western, of the zone of folding. But the greatest of all anticlines in Pennsylvania—the Nittany arch—is eccentric to the theory and contradicts Rogers's statement, for it lies on the western edge of the zone of pronounced folding, not on the eastern, and thus illustrates the fact that the undulations do not occur in regular order of size, although they are much more closely appressed at their extreme eastern than at their western limit.

The stratigraphic column of this district includes all the Paleozoic formations from Cambrian to Carboniferous, and its total varies from 18,000 to 27,000 feet. At the base is the Cambro-Silurian limestone, and above are the sandstones and shales of Upper Silurian, Devonian, and Carboniferous, in all their variety of development. Stratigraphically the beds present in composition and color variations of great interest; but in relation to structural problems they fall into only two principal divisions—the great limestone and the greater shale-sandstone series. The former is massive, little divided by vague bedding planes, —a rigid unit in folding. The latter is thin bedded, and, though some sandstone and calcareous strata are by themselves thick and hard, the entire second division resisted folding as a mass of weak beds. The influence of massive and laminated series on deformation will be discussed elsewhere, but they may be suggested by likening the great limestone to a sheet of bristol board and the shale-sandstone series to a quire of tissue paper.

Erosion has shaped from these folds the topographic types that Rogers so admirably described: The monoclinal ridge carved from the limb of a fold; the synclinal valley and mountain; the anticlinal mountain and valley. And the anticlinal mountain may be considered the characteristic feature of this topography, since it is here of common occurrence.

DISTRICT OF CLOSE FOLDING—APPALACHIAN VALLEY.

The term Appalachian valley is used by different writers to cover different areas; its broadest application is to the entire province from New York to Alabama, between the Blue Ridge on the east and the Cumberland plateau on the west. But for discussion of structure the name may be applied to the area of continuous outcrop of the great limestone formation, from eastern Pennsylvania to Chilhowee mountain, Tennessee, and from the Blue Ridge to the eastern edge of the Alleghany mountain region. As in Pennsylvania the Nittany arch, so in

Tennessee and thence southward great anticlines bring other extensive areas of this limestone to view; but their structure differs from that of the district distinguished. When so limited the Appalachian valley district corresponds to a zone of close or isoclinal folding, which is remarkable because it occurs in so massive a formation as the great limestone. Detailed studies of the structure are few and our knowledge of it is incomplete, because the uniformity of the limestone series makes it difficult to unravel the tangle of dips and strikes. But the continuous occurrence of the same strata at high dips over so large an area, taken in connection with the results of isolated studies, indicates that the folds are short, closely appressed, and intricately interfingered. Faults of moderate displacement and length accompany this folding.

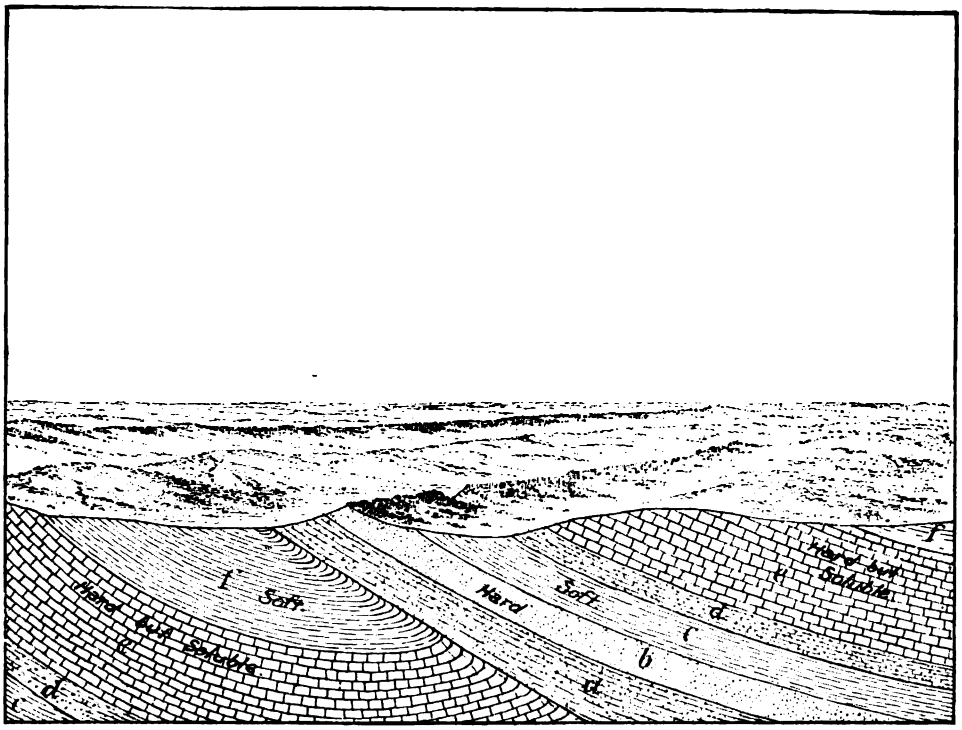
Within this area there are also several great synclinoria, which bring down below the present surface the strata of the periods following the limestone; of these synclinoria, the Massanutten of Virginia and the Bays of Tennessee are the most conspicuous; their structure is more open and their synclinal axes pitch deeper than is the case in the limestones. To them we must turn for any definite knowledge of the stratigraphy above the limestone over this area, and we there find some of the members of the upper series of the Alleghany district, but not all of them. Those Carboniferous and Devonian beds above the Hamilton, which in the Alleghanies are many thousand feet thick, are wanting in the Massanutten and in other synclinoria further south where the highest beds found are at the base of the Upper Silurian. Beneath the Cambro-Silurian limestone Cambrian shales and limestone beds are known, and shoreward they become shales, sandstones, and conglomerates.

Thus the stratigraphic column over the region of close folding is variable, but it consists of three members—a thin bedded base of unknown depth, a massive limestone 3,500 to 4,000 feet thick, and an upper series of thin bedded shales and sandstones, which rarely exceeds 5,000 feet.

Erosion has acted upon the limestone mass through chemical as well as through mechanical agencies, and the limestone areas are consequently low, and shale or sandstone areas remain relatively high. Since the limestone areas are anticlinoria and the shale areas are synclinoria, it follows that the anticlinal valley and synclinal mountain are markedly developed; they are the characteristic topographic types of the region, which is also diversified by the effects of recent and rapid corrasion of a base level that extended its plane surface over the valley.

DISTRICT OF FOLDING AND FAULTING OF VIRGINIA, TENNESSEE, AND GEORGIA.

Where the folds of the Alleghany district broaden into the simplest forms and where the close folding of the valley district passes into more gentle curves, great thrusts arise and continue thence southward.



PERSPECTIVE VIEW AND VERTICAL SECTION OF A THRUST-FAULT OR THRUST.

b is a ridge of hard sandstone which dies out as the displacement lessens and the two ranges of hills of limestone (*e*) approach.

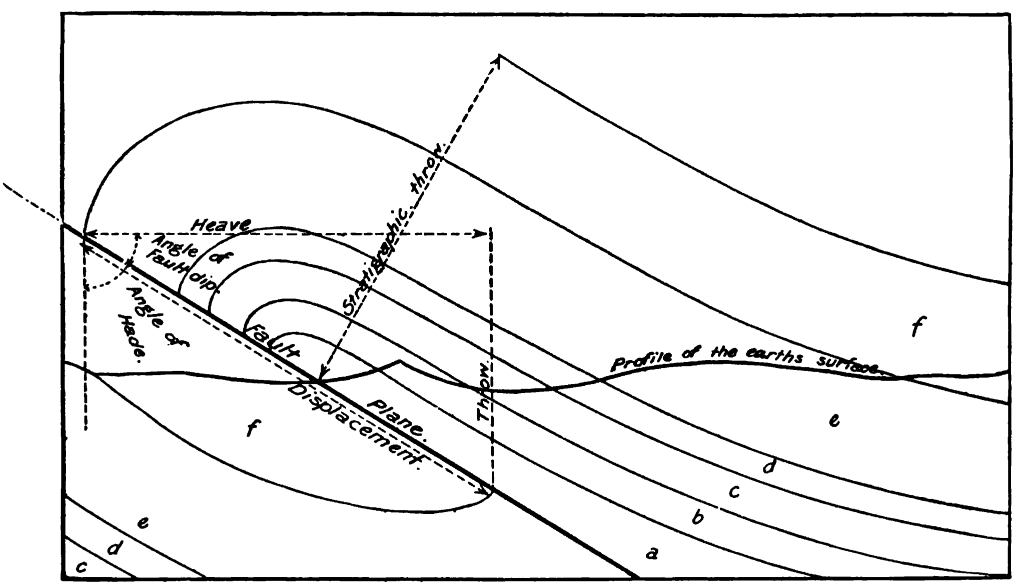


DIAGRAM OF A THRUST-FAULT OR THRUST.

These thrusts give character to a belt which extends from southern Virginia to the overlap of Mesozoic formations in Alabama. They are wonderfully persistent; they all present a fault dip to the southeast, and are in a general way parallel among themselves and to the outline of the Archean continent.

The distances across the strike between these thrusts vary from one-quarter of a mile to 10 miles, and the strips between them are sometimes of monoclinal, sometimes of synclinal structure. The faults usually arise in a simple anticline and in a longer or shorter distance the northwestern dip disappears beneath the overthrust, leaving an isoclinal southeasterly dipping structure, in which the fault dip is often parallel to the bedding of one or the other series of strata.

In regard to the relations of faults to folds we may quote from the writing of H. D. and W. B. Rogers of 1841. After describing faults transverse to the strike they say:

The other far more conspicuous class of dislocations connected with these crust undulations are the great longitudinal ones. These are of frequent occurrence in the more contorted portions of the Appalachian zone, especially in those where the chain is convex to the southeast, and in the straight sections of southwestern Virginia and eastern Tennessee. But I am persuaded from the descriptions of geologists and from my own observations that the fractures of this class are equally numerous in the Jura mountains, in the Alps, in the district of the Ardennes, in Belgium, and in the mountain chains of Scotland. A leading feature of these great fractures is their parallelism to the main anticlinal axes, or lines of folding of the chains to which they belong. They are, in fact, only flexures of the more compressed type, which have snapped and given way in the act of curving or during the pulsation of the crust. They coincide, in the great majority of instances, neither with the anticlinal nor the synclinal axis planes of the waves or folds, but with the steep or inverted sides of the flexures, and almost never occur on their gentler slopes. This curious and instructive fact may be well seen in the Appalachians of Pennsylvania and Virginia, and by tracing longitudinally any one of their great faults from its origin on the steep flank of an anticlinal wave along the base of its broken crest to where the anticlinal form is again resumed. The following brief description from our memoir on the physical structure of the Appalachians, taken from the transactions of the American Association, will show the general phases through which these fractures pass.

From a rapidly steepening northwest dip, the northwest branch of the arch (or flank of the wave) passes through the vertical position to an inverted or southeast dip, and at this stage of the folding the fault generally commences.

It begins with the disappearance of one of the groups of softer strata lying immediately to the northwest of the more massive beds, which form the irregular summit of the anticlinal belt or ridge. The dislocation increases as we follow it longitudinally, group after group of these overlying rocks disappearing from the surface, until in many of the more prolonged faults the lower limestone formation (Cambrian or Lower Silurian) is brought for a great distance, with a moderate southeast dip, directly upon the Carboniferous formations. In these stupendous fractures, of which several instances occur in southwestern Virginia, the thickness of the strata engulfed can not be less in some cases than 7,000 or 8,000 feet.

It does not appear that the Rogerses had accurate knowledge of the wonderful system of parallel thrusts extending through eastern Tennessee into Georgia, nor did Safford, who traced many of them, have a map adequate for the accurate delineation of their structural relations.

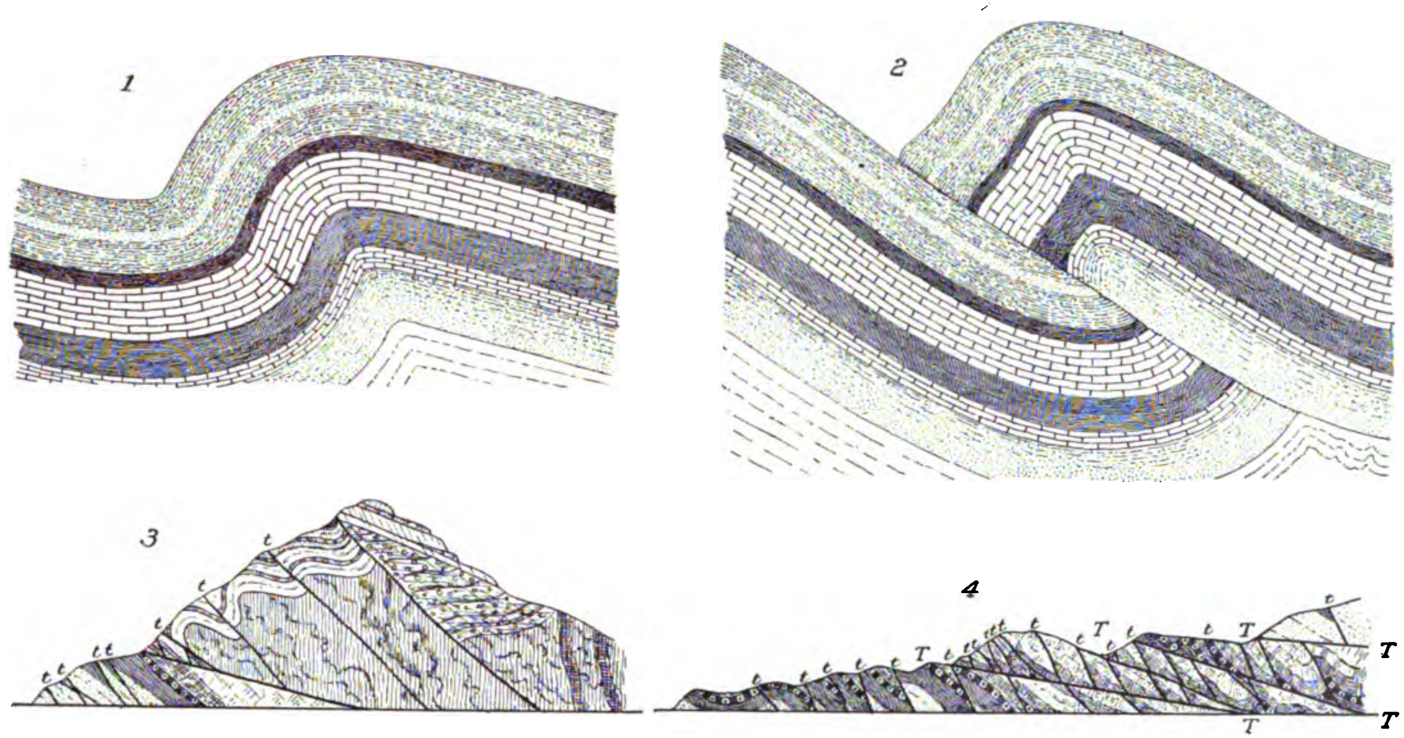
But the more recent work of the U. S. Geological Survey has mapped them from Georgia into Virginia, and the results are given on a small-scale map in Pl. LVIII. Within the area of this map there are 15 to 20 thrusts according to the distinctions made between thrusts and mere branches, with an aggregate length of about 4,500 miles. The longest single thrust extends northeast beyond the map and reaches a length of 375 miles. Inspection shows that they are intimately associated with folds, and whenever a fault fades out it is in the northwestern side of an anticline and in the direction of anticlinal pitch. This is in agreement with Rogers's observations, but his statement regarding the law of relation of thrusts to folds may be formulated with more general application, as follows: Appalachian thrusts arise in such relations to folds that the adjacent axis in the under thrust is always synclinal and the adjacent axis in the overthrust is anticlinal. But displacement may be so great as to override and bury the former, while erosion may remove all traces of the latter; hence a fault may appear between an anticline in the downthrust and a syncline in the upthrust, or between two synclinal or two anticlinal axes. When great displacement and erosion combine to destroy the evidence of folding the result is an isoclinal faulted mass.

These faults of great length, dividing the superficial crust into crowded scales, have provoked the wonder of the most experienced geologists. The mechanical effort is great beyond comprehension, but the effect upon the rocks is inappreciable. The strata beside a great fault are but rarely brecciated, squeezed or rendered schistose. The shearing planes are sharp and clean, the movement of overthrust was concentrated as by a knife cut, and the passing layers ground little grist one from another. Great vertical pressure and very slow movement probably conduced to this result, but however explained the fact is conspicuous that Appalachian thrusts are not associated with alteration of the faulted strata.

Where most numerous, ten faults lie parallel between the eastern and western edges of the belt, and thence southward they separate and some of them die out, while others pass on between flat synclines to the Mesozoic boundary. Two thrusts, the most southeastern of the group, curve through a quadrant westward and overlie the southern ends of the folds and faults with which they are elsewhere parallel. The overthrust strata along these two faults, therefore, occupy the position of deposits later than the period of deformation during which the underthrust structure developed, and the conclusion is unavoidable that an interval of erosion intervened between the faulting along a southwest strike and that along a nearly westerly strike. The possible influence of erosion on the development of the later faults has been discussed by Hayes.[1]

The strata sheared by these faults include all known horizons of the province from the lowest Cambrian to the Carboniferous, but nowhere

[1] Overthrust Faults of the Southern Appalachians, Geol. Soc. Am., vol. II, 1890, pp. 141-154.



TYPES OF THRUSTS.

1. Step-fold, showing break in the massive limestone bed which determines the plane of the break-thrust, (2), along which displacement results from further compression.
3 and 4 Examples of shear-thrusts from "Recent work in the Northwest Highlands of Scotland," by A. Geikie. 1888.
3. Horizontal section from Loch Assynt across the Silurian limestones to Cnoc an Droighinn (about three-quarters of a mile in length).
4. Horizontal section from Beallocn across Coinne-mheall to Corrie Mhadaidh (about half a mile in length).

do they bring up crystalline rocks older than the Cambrian. Physically the series is again threefold; below are the Cambrian shales and sandstones, 3,000 to 6,000 feet thick, in the middle is the great limestone 3,000 to 4,000 feet, and above are the shale sandstone formations which vary from 3,000 to 7,000 feet.

From the parallelism of the strikes and the coincidence of relief with the occurrence of hard and soft rocks arises the marked topographic characteristic of the district, the monoclinal ridge. Through scores of miles a ridge of sandstone of one horizon or another may hold its elevation and continuity, with insignificant interruptions by water gaps and by even less conspicuous though more frequent wind gaps. Another result of the peculiar structure and of its relation to the relief is the repetition across the strike of ridges and valleys shaped alternately from the same hard and soft beds.

DISTRICT OF SCHISTOSITY—SMOKY MOUNTAINS.

East of the Tennessee valley is a broad area of strata extending to the Archean shore, strata which have their lithologic representatives along the ancient continental outline as far north as New Jersey, but which are nowhere else so strongly developed as in the Smoky mountains. The rocks of the series are clastic, and they may belong to different geologic horizons in different areas; but they show a common result of metamorphism, the development of cleavage foliation in a high degree. This character distinguishes them from the other Paleozoic rocks, and taken with their semicrystalline character has led geologists to assign them to a pre-Cambrian age. Evidence is now at hand to indicate that they may be Cambrian, Silurian or later, but they were originally of peculiar composition and have undergone deformation under special conditions. The result of this deformation is intimate folding without faulting, but with much cleavage foliation.

THE STRUCTURAL PROBLEM.

The structural problems of the Appalachian province are indicated in the brief description of these four districts. It is observed that the strata have been tangentially compressed and the cause of that compression is the ultimate question. We can only know the force by its effect and we must clearly understand the determining conditions before we can approach the unknown cause. Let us reconsider the facts:

In order of development it has been usual to recognize the open fold, the closed fold, and the fault. How are these related to each other? Are they necessary stages of deformation from the flat strata to the last expression of the force? The open fold must precede the closed, but need one anticline close before the pressure can raise an adjacent one? Must faulting ensue when flexure reaches a definite phase? Over a large area many open folds lie side by side; clearly, conditions existed which permitted or required the growth of several arches simultaneously or the

force failed to close one fold before it caused another; so continued compression may not close an open fold. Again over the valley district, where closed folds prove great compression, faults are few; yet they are numerous in the zone of comparatively moderate folding farther south. If the phase of folding in the latter area was alone appropriate for faulting, why did the strata in the valley district pass through it unfaulted? The fact stands as proof that faulting arises from some conditions more or less independent of the phase of folding; it is conceivable that faults may sometimes be independent results.

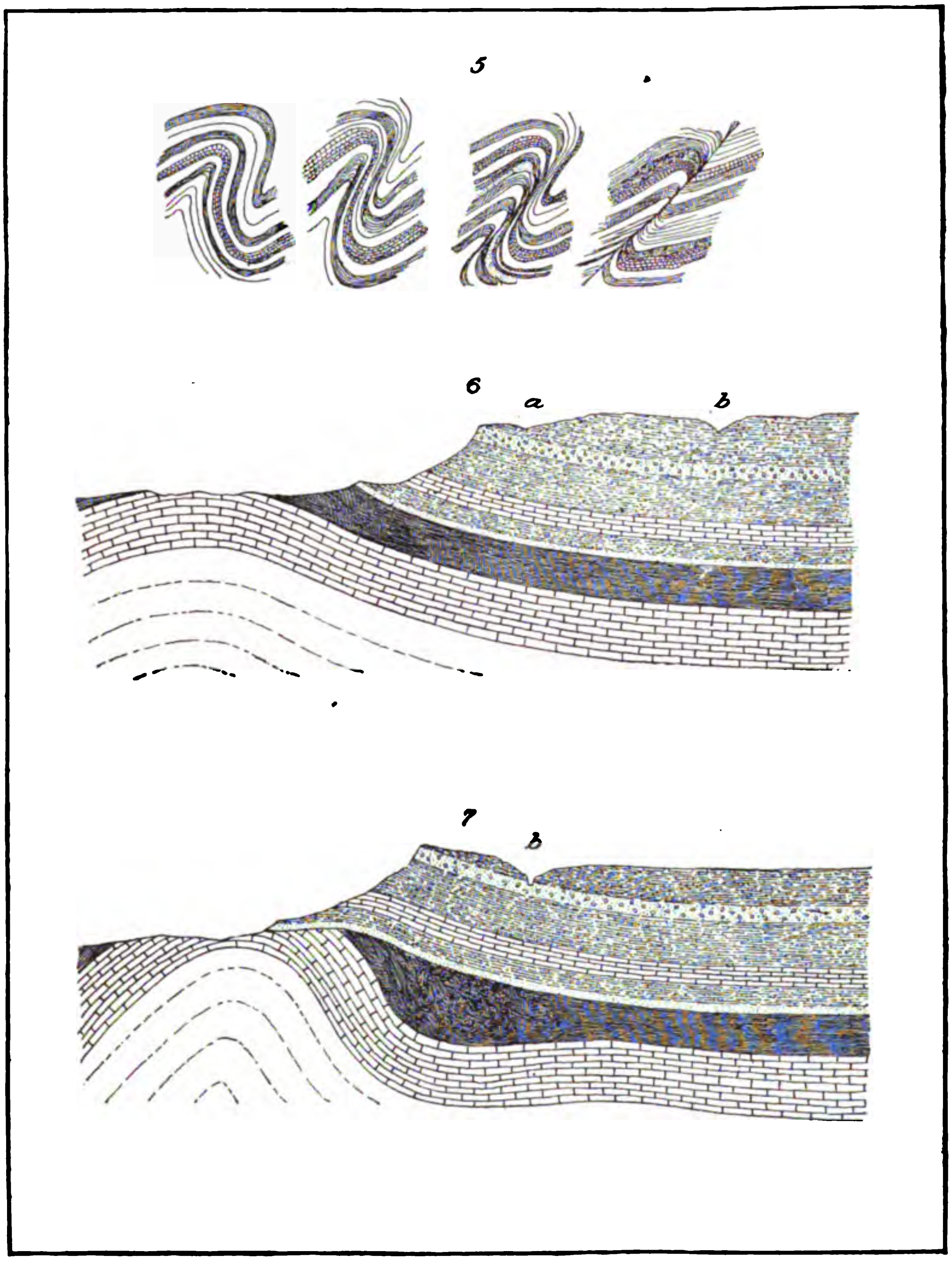
Folds lie here side by side, parallel, one far larger than its fellows, the others among themselves approximately of the same magnitude. Such are the relations of the Nittany arch to the group of minor folds southeast of it. And related to these is the Broad Top coal basin, a gently flexed syncline. What condition located and limited the Nittany fold? Why is it greater than its foot-folds, as a mountain range is higher than its foothills? Why did the Broad Top basin escape or resist compression that raised the anticlines which pitch into and die out in it? Or in the far southern field, what condition determined the parallel but widely separated anticlines of Alabama?

Over the entire province there is likeness of phenomena which argues unity of cause, but there is variety of effect, which suggests unlikeness of conditions. The conditions antecedent to deformation were the result of sedimentation. Does the distribution of strata afford any answer to the questions raised? The sedimentary deposits of the province are capable of threefold division: there is a laminated base, a massive middle, and a laminated top. The dominant fact of stratigraphy is the continuous limestone—the middle member—hard, resistent, relatively inflexible; it was the stratum which might best transmit a compressing force and would bend or break under increasing pressure or along a line of weakness. If a strut shall be strong it must be straight; crooked, it bends or breaks at the crook. Was the great limestone a plane or did it depart from horizontality—the direction of thrust? The uppermost member varies from one mile to four miles in thickness in the extent of the province. Were these variations rapid enough to cause deflections in the great limestone? Where the great Devonian and Carboniferous sediments give the upper members the maximum weight, folding is the type of deformation; where these strata are thin, faulting dominates. Was there relation between the load borne by the great limestone and the resulting type of deformation?

Questions like these suggest a general hypothesis that circumstances of sedimentation determined conditions which afterward controlled the place and type of deformation and influenced the size and relations of individual structures.

EXPERIMENTAL RESEARCHES.

The fact of compression is so patent in folded regions, the action of a force against the edges of the strata is so clearly suggested, that



TYPES OF THRUSTS.

5. Stretch-thrust (Faltenverwerfung) developed from an overturned fold by stretching of the middle limb (after Heim).
6. Erosion-profile and section of a simple anticline.
7. Erosion-thrust developed from the condition shown in 6 by compression from the plateau side, accompanied by continued erosion.

many geologists have been tempted to seek a ready solution of the problems of structure by imitative experiments. To put layers of sand, clay, plaster, or even cloth into a box and compress them endwise . . a very simple operation, and the resulting plications often bear a likeness to the folds observed in rocks; but it is the lesson of experience in many directions that it is less difficult to imitate one of nature's processes than to understand either the imitation or, through it, the original. For this reason some have cast experiments aside as useless and others have been content to describe their unexplained results. Nevertheless two geologists have through experiments successfully attacked the problem of deformation by compression, Schardt and Cadell; and others whom I do not know of may have passed from the imitative to the explanatory stage of this study. The work of these two investigators became known to me only after my own experiments had led me to results in some cases in agreement with theirs. Thus, in so far as we have reached similar results, the conclusions carry the weight of independent corroboration. Some quotations may illustrate the methods and results of the more important experimental studies of which I have knowledge.

The first efforts to simulate the forms of folded strata by experiments with plastic materials were made as far back as 1812 by Sir James Hall, who presented a communication on the subject to the Royal Society of Edinburgh on February 3 of that year. His attention had been attracted by the folds exposed in the lofty cliffs on the coast of Berwickshire, England, of which he gives sketches with diagrams of their eroded and subterranean portions; the latter indicate that he interpreted the connections of the folds in the same manner that they have since been understood by later geologists.

He says [1]:

It occurred to me that this peculiar conformation might be accounted for by supposing that these strata, originally lying flat and in positions as nearly level as might be expected to result from the deposition of loose sand at the bottom of the sea, had been urged when in a soft but tough and ductile state by a powerful force acting horizontally; that this force had been opposed by an insurmountable resistance upon the opposite side of the beds, or that the same effect had been produced by two forces acting in opposite directions, at the same time that the whole was held down by a superincumbent weight, which, however, was capable of being heaved up by a sufficiently powerful exertion.

By either of these modes of action I conceived that, two opposite extremities of each bed being made to approach, the intervening substance could only dispose of itself in a succession of folds, which might assume considerable regularity and would consist of a set of parallel curves alternately convex and concave towards the center of the earth. At the same time, no other force being applied, any two particles which lay with respect to each other so that the straight line joining them was horizontal and at right angles to the direction of that active force, would retain their relative position, and of course that line would maintain its original straightness and horizontality; and thus, the forces exerted being simple, or, if compound, tending, as just stated, to produce a simple result, the beds would acquire the simple curvature * * * which belongs to them in the immediate neighborhood of

[1] Trans. of the Royal Society of Edinburgh, vol. vii, 1815, p. 84.

Fast Castle; whereas in Galloway and some parts of our coast, particularly near Gun's Green, to the eastward of Eyemouth, where the curvature deviates from that simple character and becomes in the utmost degree irregular, we must conceive the force to have been more complicated or most probably to have acted at successive periods.

This conjecture no sooner occurred than I endeavored to illustrate my idea by the following rude experiment, made with such materials as were at hand. Several pieces of cloth, some linen, some woollen, were spread upon a table, one above the other, each piece representing a single stratum; a door (which happened to be off the hinges) was then laid above the mass, and being loaded with weights, confined it under considerable pressure; two boards being next applied vertically to the ends of the stratified mass were forced towards each other by repeated blows of a mallet applied horizontally. The consequence was that the extremities were brought nearer to each other, the heavy door was gradually raised, and the strata were constrained to assume folds bent up and down, which very much resembled the convoluted beds of killas, as exhibited in the crags of Fast Castle, and illustrated the theory of their formation.

I now exhibit to the society a machine by which a set of pliable beds of clay are pressed together so as to produce the same effect, and I trust that the forms thus obtained will be found by gentlemen accustomed to see such rocks to bear a tolerable resemblance to those of nature, as shown in Fig. 6, copied from the forms assumed in the machine by an assemblage of pieces of cloth of different colors.

In 1878, M. Alphonse Favre, proceeding upon the hypothesis of a cooling nucleus which fails to support the hard outer crust of the earth, undertook some experiments with beds of clay subjected to contractive forces. Upon a stretched rubber band he placed a mass of clay from 25 to 26^{mm} thick, and allowed the rubber slowly to resume its proper length, carrying with it the mass of clay. In order that the clay should not slip upon the band of rubber, pieces of wood were attached to the ends, and thus the compression produced was in effect similar to that produced by Sir James Hall in his machine; but the materials of Sir James Hall's experiment were rigidly confined above, and the deformation of the upper surface was controlled by the cover. In M. Favre's experiments this upper surface was able to rise into ridges, and he obtained anticlinal and synclinal forms which bear a certain resemblance to those observed by geologists in the contorted strata of the Alps and other folded regions. The masses of clay employed by M. Favre were not divided by structure planes and acted simply as a homogeneous bed, yielding at the surface more completely than at the bottom simply because less confined. The description of the several experiments is published, with a discussion of the theories of mountain building, in the Bibliothèque Universelle.[1]

In 1884 Mr. Hans Schardt, having studied the geology of a portion of the Pays-D'Enhaut Vaudois, in the western Alps, was led to attempt the explanation of various structural facts by means of experiments with masses of clay and sand compressed in the same manner as in the experiments of M. Favre; but M. Schardt took a step beyond the theories of M. Favre, and attributed the character of individual structures and the differences observed between structures in different regions

[1] Archives des Sciences Physiques et Naturelles, No. 246, 1878.

to the nature of the strata in which they were produced. He was therefore not content to compress a single layer of plastic clay, but he made up the piles from various hard and soft layers of damp clay and of clay mixed with sand. I quote those statements[1] which I have had the pleasure of corroborating:

The earth's crust is not an homogeneous layer, but is a complex of layers of varied nature. It is therefore necessary (in experimenting for geologic structures) to multiply the beds of clay, and to vary their consistency, in such a manner as to represent in miniature the great strata of the mountains. * * *

The first experiments were not crowned with the expected success. It is, indeed, very difficult to cause beds of clay of unequal hardness to adhere to each other. The bed of hard clay separates from the lower clay and forms hollow arches, in spite of the weight of soft clay which covers it. In nature the beds can scarcely separate, as they are subject to the action of weight, which does not act with the same importance in experiments on so small a scale. It was therefore necessary to replace this factor by the adherence of the beds among themselves. I accomplished this by placing between the layers of ordinary clay a small quantity of kneaded clay which was fine and tenacious. This method at the same time permitted the beds to slip one upon the other without separating. In nature the slipping of strata upon their bedding planes seems ordinarily to be produced when the beds are strongly bent. This kind of dislocation has certainly great importance, which has not always been sufficiently recognized.

In nature this adherence is replaced by the weight. It is unquestionable that the pressure of the upper beds upon the lower must be enormous at a certain depth. Now the moment that a compact calcareous bed begins to form an arch, the pressure which the upper beds exert upon the lower beds through this compact bed ceases exactly at the place of the anticlinal curve; it acts only at the two sides of the arch which suffices to force the lower soft beds to follow the fold of the compact bed and to conform exactly to its concave curve, in the same manner that a soft mass will pass between the fingers when it is pressed against the hand. Still more should this be true as the pressure, which acted previously equally over the entire surface, is localized and consequently increased toward the synclinal curves, where the upright legs of the arch, which must actively raise the superposed soft strata, find their points of support. All the experiments upon the action of compression show clearly this fact.

The effects of compression vary with the position of the beds. When they are horizontal and the pressure acts in the direction of the stratification, the resistance attains its maximum; but when they commence to form an arch, the pressure, which is transmitted always in the direction of a tangent,[2] acts obliquely to the stratification until the beds become vertical. From that time the pressure acts transversely to them; thence it follows that they are thinner on the legs of the folds than on the axes of curvature; they appear to have been laminated or flattened by the compression.

The opposite is produced, on the contrary, when there is a reaction of a hard bed upon a soft bed; then the latter is thinned around the convex curve of the hard bed.

I have thus far spoken of the case where a single hard bed was inclosed between two soft beds. But if experiments are made with a complex of beds alternately harder and softer. it will be found that all the hard beds are at the same time conductors of the compression proportionally to their thicknesses and consistencies. When there is folding their effect is combined and the plastic beds are simply carried with them in the rearrangement.

In February, 1888, the Royal Society of Edinburgh, before which

[1] Geological studies in the Pays-D'Enhaut Vaudois by Hans Schardt; Bull. de la Soc. Vaudoise des Sci. Nat., vol. xx, 1884, pp. 143–146.

[2] It will be seen later that I differ from M. Schardt in regard to the direction in which pressure is transmitted. B. W.

Sir James Hall had presented the first article on experiments of this nature, received a paper from Mr. Henry M. Cadell, on "Experimental Researches in Mountain Building." The purpose of Cadell's experiments was to simulate the "behavior of brittle rigid bodies, which, instead of undergoing plication when subjected to horizontal compression, had snapped across and been piled together in great flat slices like so many cards swept into a heap on a table." To this end he used plaster of Paris interstratified or mixed with layers of sand, and in some experiments black foundry loam and clay.

The experiments were of three distinct kinds. The first series (A) was designed to explain the behavior of different types and arrangements of strata when pushed horizontally over an immovable surface. The object of the second series (B) was to ascertain, if possible, how gently inclined thrust planes may have originated, and to trace their connection with "fan structure and other phenomena observed in mountain systems of elevation." The third series (C) was conducted on principles suggested by the experiments of Favre, and Favre's experiments were extended "by removing the upper layers of the wrinkled clay and observing the effect of the contraction on the deep-seated portions of the miniature mountain system."

The apparatus used by Cadell was a strong wooden box, in which pressure was applied to a removable end by means of a screw. The strata were subjected to no load but that of their own weight, and the conditions of the experiments simulated those of rocks at or near the earth's surface. The summary of his results is as follows:

(1) Horizontal pressure applied at one point is not propagated far forward into a mass of strata.

(2) The compressed mass tends to find relief along a series of gently inclined "thrust planes," which dip toward the side from which pressure is exerted.

(3) After a certain amount of heaping up along a series of minor thrust planes, the heaped-up mass tends to rise and ride forward bodily along major thrust planes.

(4) Thrust planes and reversed faults are not necessarily developed from split overfolds, but often originate at once on application of horizontal pressure.

(5) A thrust plane below may pass into an anticline above and never reach the surface.

(6) A major thrust plane above may, and probably always does, originate in a fold below.

(7) A thrust plane may branch into smaller thrust planes, or pass into an overfold along the strike.

(8) The front portion of a mass of rock being pushed along a thrust plane tends to bow forward and roll under the back portion.

(9) The more rigid the rock the better will the phenomena of thrusting be exhibited.

(10) Fan structure may be produced by the continued compression of a simple anticline.

(11) Thrust planes have a strong tendency to originate at the sides of the fan.

(12) The same movement which produces the fan renders its core schistose.

(13) The theory of a uniformly contracting substratum explains the cleavage often found in the deeper parts of a mountain system, the upper portion of which is simply plicated.

(14) This theory may also explain the origin of fan structure, thrusting, and its accompanying phenomena, including wedge structure.

The conclusion expressed in paragraph 9 was deduced from the experiments with rigid materials. By reference to Plates XCV and XCVI it may be seen that like effects are produced in butter-like substances under heavy load.

We may now turn to the theoretic considerations which governed the experiments of which this paper is partly a result.

PROBLEM OF STRUCTURAL EXPERIMENTS.

To bend, to break, to shear, these are purely mechanical operations. They require the application of a force external to the material bent, broken, or sheared, a force which overcomes the internal resistances. The processes of terrestrial folding and faulting involve these three operations and obey mechanical laws. The problem which the facts present is to ascertain: (1) what was the initial character and arrangement of the strata folded and faulted, and what consequently were the internal resistances; (2) under what conditions was the external force applied, and how was it transmitted; (3) what possible origin can be assigned for a force which is qualitatively and quantitatively sufficient to produce the observed results.

Mechanical laws do not vary with the magnitude of the active forces nor with that of the passive resistances; of a series of strata hundreds of feet thick and of a pile of layers only inches thick, the bending, breaking, or shearing will obey the same laws, if all the factors of pressure and resistance are proportionate in each case to the dimensions of the pile, and the similitude of results will be the closer the more exactly the conditions in the one case represent those in the other. If, then, we can make a reasonable analysis of the character and arrangement of the strata deformed and of the conditions governing deformation, we may be able experimentally to produce structures under conditions so similar to those of nature that the forms shall be of the same kind as are observed in strata, and with analysis thus confirmed by synthesis we may approach the problem of the origin of the sufficient force with more confidence.

The principal difficulty in this analysis is to comprehend the relative proportions of the elements of the problem. The masses involved are so extensive, the forces required are so utterly beyond expression in our foot-tons, that our usual conceptions of rock strength and of rock rigidity are worthless. In our constructions, opposed to our forces, to our tools, stones are hard, firm, unchanging, and the saying is "hard as a rock," but in resistance to forces of the earth's mass, this same rock may be relatively soft as wax. To arrive at a fair idea of conditions beyond our ordinary experience, we may consider the nature of the support of the earth's crust. Let us look upon it as the problem of a stone bridge. If an engineer wishes to span a culvert 5 feet wide, he may find a single flat stone to throw across. For a span of 50 feet he

must build an arch; for 500 feet the arch must be so high and the masonry so massive that the structure is seriously weakened by its own weight. Increase the span and the construction ultimately becomes impossible; the weight of material required soon exceeds the crushing strength of the stone, and, however well proportioned, the structure must crumble as though built of sand. Now limit the engineer to an arch whose rise shall be 8 inches in a span of 1 mile—that is, limit him to the curvature of the earth. Is it conceivable that an arch, even of solid granite, a mile in span and 8 inches in rise, should be self supporting? Obviously not.[1] But the terrestrial crust, of which any arc is an arch of these proportions is composed of heterogeneous materials, some of them weaker than granite, and where granite falls short of self-support, the crust as a whole must fail. Hence, however thick we conceive the rigid outside shell to be, it rests with all its weight upon whatever lies within it.

As this statement is true for each layer of the earth's crust, at the surface and below it, it follows that the pressure due solely to weight increases from the surface downward; and as the attraction of gravity also increases in the same direction to a certain depth, the growth of this pressure is more than proportional to the depth below the surface. It is not necessary here to enter into the mathematical discussion of the relations of gravity, density, and pressure, but the following table gives the figures, according to the Laplacian hypothesis, as calculated by Mr. R. S. Woodward.

Variation of terrestrial density, gravity, and pressure according to the Laplacian law.

[By R. S. Woodward. 1890.]

Depth in miles.	Density.	Acceleration of gravity.	Pressure in atmospheres.	Pressure in pounds per square inch.
0	2.75	1.0000g	1	15
1	....	....	400	6,000
2	....	....	800	12,000
3	....	....	1,210	18,150
4	....	....	1,620	24,300
5	2.76	1.0006g	2,020	30,300
10	2.78	1.0012g	4,200	63,000
15	2.79	1.0018g	6,390	95,850
20	2.81	1.0024g	8,600	129,000
50	2.89	1.0060g	22,000	330,000
100	3.03	1.0116g	45,300	679,500
500	4.18	1.0379g	236,000	3,540,000
560	4.36	1.0389g	318,000	4,770,000
610	4.50	*a*1.0392g	354,000	5,310,000
660	4.65	1.0389g	391,000	5,865,000
1,000	5.63	1.0225g	672,000	10,080,000
2,000	8.28	0.8312g	1,700,000	25,500,000
3,000	10.12	0.4567g	2,640,000	39,600,000
3,959	10.74	0.0000g	3,000,000	45,000,000

a This is the maximum value, and the corresponding depth; 610 miles is the depth at which a given mass would have the greatest weight.

[1] Physics of the Earth's Crust, Rev. Osmond Fisher, Chap. iv, 1st ed.

Clearly to comprehend the meaning of the figures in the last column of this table, consider the problem of support of the earth's crust as one of stability of a great structure. The engineer who would build to great height must have a secure foundation. If he build on yielding sands there is a narrow limit to the weight of the structure which can be sustained; if the foundation be granite there is also a limit beyond which the weight of the towering shaft will crush the support. Now the problem is not materially different if for height above the earth's surface we substitute depth below it. The crushing strengths of stones at the surface vary as follows:

	Pounds per square inch.
Granite	7,000 to 22,000
Limestone	11,000 to 25,000
Sandstone	6,000 to 14,000

These values probably increase with depth in the earth's crust and in an unknown ratio; but it is not likely that the increment of strength is as great as the increment of pressure. Mr. Woodward's table shows that at 5 miles below the surface the pressure exceeds the maximum resistance of rocks at the surface, and at 10 miles the pressure is more than double the resistance. This means that somewhere between 5 and 10 miles beneath the surface the weight of the superficial crust is sufficient to crush its support.

But crushing is not possible within the earth's mass in the way in which we see it at the surface. To crush is to separate into incoherent particles; and irresistible confinement, itself due to the pressures which are greater than coherence, holds any deep-seated rock mass to its coherent volume. In this condition, confined under pressures greater than its crushing strength, a substance may be said to be latently plastic. The cohesion between its particles is unimpaired, fracture or crushing into separated grains is impossible for want of space; but change of form may be induced by a sufficient disturbing force, and such change is plastic flow. The conception of this latent plasticity needs to be clearly understood. It is a mechanical condition, the result of external forces which are strong enough to overpower cohesion. It is not a plasticity due to internal tension like that of hot iron, for the temperature at a depth of 5 miles is probably not sufficiently elevated to modify greatly the firmness of rocks. The average rate of increase of temperature beyond the local unchanging mean of 51.3° Fahr. is 1° for every 75 feet, as recently determined in the well at Wheeling, West Virginia, to a depth of 4,500 feet. If we may assume that this rate continues to some depth, we should have at 5 miles below the surface a temperature of only 421°. It is not probable that the assumption is strictly valid, and the temperature may be considerably higher, but it can scarcely approach the melting point of rocks, which varies from 1,200 to several thousand degrees Centigrade. The independent evidence of stratified rocks, known to have been buried

20,000 to 30,000 feet in the crust and now exposed by erosion, bears on this point. Such strata are solidified by pressure, but have not suffered chemical metamorphism, as they must have done had they been heated to plasticity.

We may fairly conceive the earth's crust to consist of a superficial shell 5 to 7 miles thick, which rests upon and grades in substance and physical condition into a subjacent shell. The under is only differentiated from the upper by its relative position in consequence of which it supports a crushing load and forms a latently plastic foundation; and that immobility of the surface which is expressed in the phrase of "terra firma" depends upon the equality of the inert resistance to the downward pressure. Destroy that equality by increasing the pressure over one area beyond that at another until the strength of the rock is overcome, and there must result an adjustment of weights and supports in such wise that the latently plastic foundation flows from the greater toward the lesser load—that is to say, the earth's external mass is in a condition of hydrostatic balance. For this condition Dutton proposed the term isostatic, and he coupled the idea of isostatic adjustment with a theory of folding,[1] a theory to which we shall recur later. We have thus taken the first step in the analysis of our problem: The strata which have suffered folding and faulting floated upon and graded downward into a latently plastic mass.

In speaking of the earth's crusts resting upon a plastic support, it is easy to imply that the shell is homogeneous and distinct in character from the support. Neither implication is correct. That part of the earth's mass which it is convenient to call the crust can not be divided off from the spheroid within except by an imaginary boundary; and this same crust can not be regarded as homogeneous except by a disregard of plain facts. The consideration of the relations of its great rock types among themselves and of the resistances they respectively offer against earth-deforming forces forms the second step in the analysis of our problem. We need take account only of extensive bodies, and we may divide rocks simply into massive and stratified; the former may include great crystalline masses, either metamorphosed sediments or igneous rocks, and also closely folded stratified series; the latter consists simply of the flat-lying sediments. The distinction to be recognized between them is a difference of rigidity, and it is very like the difference between a heavy beam and the same wood sawed into boards. The beam resists a pressure which bends the pile of boards, and massive rocks are immovable in relaion to a force which folds strata. To deform a massive rock requires that the cohesion of the particles in the mass shall be overcome and a rearrangement effected which results in schis-

[1] On some of the greater problems of physical geology. C. E. Dutton, Bull. Phil. Soc. of Washington, vol. XI, pp. 51, 64.

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tosity. To deform stratified rocks demands that beds shall slip past one another and bend; the friction among beds and the interstitial resistances of different beds to folding are much less than the cohesive forces of a solid mass. It follows that strata are more easily deformed than masses, and if the two rock types sustain common compression the stratified series suffers the major deformation. Therefore when compression follows a period of deposition, and affects simultaneously a continental area of massive rocks and the adjacent area of sediments, it is in the sediments that we may most clearly observe the effects. The zone of folding and faulting may be miles in width and include anticlines of great height; the zone of schistosity may be but a few scores or hundreds of feet wide, and be masked by complex relations with the results of earlier actions of the same kind. The changes of form are precisely what would result from pressing a pile of sheet-iron irresistibly against a mass of soft but solid iron. The sheets may be bent while the mass is but bruised.

If the preceding statements are clearly grasped, we may proceed to consider the arrangement and characteristics of strata, with a view to understanding better the deformation of stratified rocks alone. In the Appalachian province strata have a maximum thickness of 30,000 feet near shore along a very narrow zone and thin away rapidly toward the west to less than 10,000 feet. These thicknesses are great, measured by our standards, but compared with the width of deposits they are but moderate. If the horizontal extent be represented by the width of this page, one hundred leaves will compare in thickness with the maximum of sediments; and it is obvious that a broad pile of strata, whose aggregate is relatively so thin, is rather flexible than rigid. As the beds would not sustain their own weight over any span of miles, so they would transmit a great force only while it coincided with their plane.

This idea of flexibility is strengthened by two considerations: such a mass of strata is not divided into a hundred but into thousands of layers, and great subdivision weakens it; and furthermore, in folding, the strata do not yield as parts of a simple mass, but resist individually and irregularly. Reference to the columnar sections of strata in the Appalachian province will show how heterogeneous is the pile in a vertical direction, and how varied are the deposits in adjacent parts of the same district. There is every class of sedimentary deposit: Conglomerate, sandstone, shale, and limestone, with gradations from one into another, giving an indefinitely varied series. Each bed of such deposits is, in relation to others, more or less flexible, more or less frangible, and the relative flexibility and frangibility of the principal members of a series have an important influence in determining the result of deformation. Flexibility is a direct function of lamination and toughness of the layers; its opposite, frangibility, is directly proportioned to the thickness and incoherence of the stratum. The following

column read downward expresses the order of flexibility; read upward, that of frangibility of lithologic varieties:

Less frangible thick to thin bedded.	Argillaceous shales.	Less flexible thin to thick bedded.
	Calcareous shales.	
	Arenaceous shales.	
	Limestones.	
	Sandstones.	

Such a statement needs to be qualified by considerations of modifying conditions; of these, pressure and confinement are the most important, and, as we have already seen, they are effective in the earth's mass roughly in proportion to the depth below the surface. In discussing the support of the superficial crust we took account of depths at which pressure renders the rocks latently plastic; but pressure is an important condition far above that zone in the crust itself. The distinction between a frangible and a flexible stratum is that in process of deformation the particles of the former separate beyond the radius of cohesion; those of the latter do not. Pressure and confinement prevent this separation of the particles of an otherwise frangible mass and force it into a state of flexibility. Thus it is possible to explain that rocks which are brittle at the surface bend like iron within the crust; and thus we may comprehend that a thick stratum may fold without fracture in one district under great load and break in another district under less load. We may express this idea by saying that the flexibility of a layer is a function of its depth in the earth's crust, or of the load which the stratum bears;[1] and it follows that in an assumed homogeneous deposit of great depth the change from rigid beds at the surface to flexible beds at the base would be a gradual and continuous one. This assumption is never true for any depth. Deposits of strata are not homogeneous except in moderate thicknesses, for the alternation of shales, sandstones, and limestones in ever changing association is the rule, and with the lithologic changes go changes in rigidity. Near the top all are more frangible, toward the base all are more flexible, but from top to bottom each bed is different in frangibility or flexibility from its neighbor under like conditions.

The deforming force which folded Appalachian strata was one of compression, acting tangentially to the earth's circumference. The physical conditions necessary for such action are that an arc of the earth's mass shall shorten, and that this shortening shall take place in such manner as to restrain the superficial crust within the lessening length of the arc. We may conceive the strata confined between two crystalline masses as between two comparatively immovable buttresses, or as settling against one such buttress in consequence of movement

[1] G. K. Gilbert, Henry Mountains, p. 83.

of the stratified mass; but however we think of the force applied it is evident that it must be transmitted in the stratified rocks, and the mode of this transmission will affect the result of deformation. A push against one edge of a piece of bristol board reaches to the further edge; it does not to the same degree extend across a strip of tissue paper. So a thrust against a massive limestone may be effective at long distance from its origin, while the same force would be shortly expended in a thickness of shales. Again, a strut which is restrained from deflection by guides is stiffer than the same strut free to bend. So a stratum confined beneath a superincumbent load will more rigidly transmit a compression than the same bed near the surface. Thus, two conditions directly influence the transmission of a thrust tending to produce deformation; the one is lithologic character and massiveness of bedding; the other is the amount of load on the transmitting stratum.

The analysis of the conditions governing deformation of strata is thus carried theoretically as far as it safely can be. We have determined that: (1) the support of the superficial crust is latently plastic; (2) if massive and stratified rocks suffer like compression, the latter will exhibit the greater deformation; (3) the relation of thickness to extent of stratified rocks is such that the mass as a whole is flexible rather than rigid; (4) flexibility and frangibility, as applied to strata, are related in opposite ways to the thickness of the stratum and its toughness; and they may for one stratum be exchangeable according to the load it supports; (5) the transmission of a thrust tending to deform is a function of the firmness of any stratum and of the load upon it.

The synthetic study of the structural problem demands conditions similar to those of the earth's crust, and resistances which, in proportion to the force at command, are similar to those overcome by the terrestrial compressive strain. The conditions indicated by the preceding analysis, as necessary to successful experiment, are: (1) strata of such thinness in relation to their length as to fall far short of the rigidity required to support their own weight in a horizontal position; (2) a plastic support for these strata; (3) means of compressing the strata endwise. The forces at command for compression are necessarily of moderate power, and their capacity to deform must be greater than the resistance to change of form, hence the strata must consist of materials which are but moderately coherent, although firm. Furthermore, since strata in the crust pass through a wide range from frangibility to plasticity, the materials experimented with must be capable of like variations.

The substance chosen as most nearly possessed of the requisite qualities was beeswax, and its character was varied by adding other substances. Plaster of Paris to harden, and Venice turpentine to soften it, were adopted after trial of various materials, and with these added in different proportions, separately or together, the range of quality from

brittle solid to semifluid may be covered. But when a mixture has been adopted as a standard by which to test any hypothetical condition, the temperature of the model must be kept approximately constant at successive stages of the experiment, since the plasticity of wax and turpentine is influenced by heat. If the wax be melted and the other substances be stirred in, the mixture can be cast into layers of any desired thickness, and these when cold can be arranged to simulate any given stratigraphic column.

The combination of weakness with reasonable firmness is fairly well obtained in strata so cast and piled; but the condition of plasticity in a high degree is not consistent with the stability of models which may be kept during days or weeks. Plasticity in the earth's crust is a result of pressure due to load, and if we can reproduce that condition during experiment, we may use materials which retain their form under ordinary circumstances. The load by which this is accomplished must be above the strata undergoing compression, and of such a nature that it will not interfere with the movement of the beds. In some respects mercury would be an ideal substance, but it is too difficult to handle and might cause buoyant strains of an undesirable character. A body of shot is at once heavy and yielding and has been found convenient to handle. Artificial conditions are introduced by such a load, as may be seen by reference to the illustrations of experiments, but they are easily observed, and no better means of representing vertical terrestrial pressures has yet been suggested. A maximum weight of 1,000 pounds has been used, evenly distributed over the models, giving a pressure of 5 pounds per square inch.

The machine used for compressing the piles of strata endwise is a massive box of oak provided with a piston which can be advanced by a screw. Several forms of this box have been tried, and that which is most convenient is represented in plate LXVI. The pressure chamber is 3 feet 3⅜ inches (1 meter) long and 6 inches wide. The sides are removable, but are strongly bolted together during an experiment. The block which carries the screw and that against which the model is pressed are both bolted to a base which is stiffened by braces, and as other bolts which hold the sides in place pass through these blocks the distance between them is rigidly fixed. The piston is a massive box of oak, and the screw is so attached as to advance or withdraw it. The depth of this pressure box is only a foot, but when a model is in place additional height for the shot may be obtained by putting on frames that fit closely.

Given the materials, the load, and the pressure box, the making of an experiment involves the assumption of conditions of stratification, the casting and arrangement of strata in accordance with the assumption, and the compression of the resulting pile. The layers will usually be arranged with the expectation of producing some definite structural form, a fold or a fault, and the result of compression is the test of the

hypothesis. Whether this be confirmatory or not it is desirable to know the progress of deformation, since this knowledge is an important aid toward improvement in assumptions and methods, and to secure this the compression is carried forward step by step, and the stages of shortening are successively photographed. These photographs furnish the accompanying illustrations. (Pls. LXXV to XCVI.)

The assumptions may be systematized and the experiments may be arranged accordingly. In beginning this research, in 1888, the general questions proposed were:

(1) What is the influence of stratigraphy?

(*a*) How do thin beds fold independently?

(*b*) How do thick beds fold independently?

(*c*) How do thick and thin beds fold combined in different vertical relations?

(*d*) How do thick and thin beds fold combined in different horizontal relations?

In order that the results of experiments based on these four queries may be comparable, the consistency of the materials used should be constant for a series from (*a*) to (*d*).

(2) What is the influence of load? To answer this the preceding tests should be repeated under different loads.

(3) Is the influence of plasticity the same as that of load? This may be tested by repeating the arrangement of strata in different materials and compressing under a constant load.

Putting these questions more concisely, we may say: Given three variables, stratification, load, and consistency, if any two be assumed constant, how will the variation of the third affect the result of deformation?

It was supposed that this was a complete statement of the structural problem; but difficulties soon arose in the mechanical management of the experiments and in the interpretation of results. These have led the inquiry from the direct course proposed, and the divergence has been found fruitful in hypotheses. The mechanical difficulties were two: The stresses developed in compressing the models proved to be unexpectedly great, and several boxes were burst in the early trials; and, again, friction of the plastic substances against the box sides was found to be a serious and artificial condition. The machine herewith illustrated has proved strong enough for experiments with models of firm substances, but even it has yielded so as to modify the amount of compression which a model was supposed to have suffered. Friction between the model and box has been practically abolished by introducing a layer of shot around the model; to accomplish this the layers are cast an inch narrower than the box, and the pile is placed upon shot, while the half inch space on either side is similarly filled.

After a number of experiments I began to be embarrassed to explain the constant occurrence of an anticline at the end of the model nearest

the piston, and the question became prominent: How is the thrust transmitted through the model? The answer, when reached, suggested new hypotheses of conditions controlling deformation, and the discussion can be adequately treated only under a distinct heading.

THEORY OF STRAINS UNDER EXPERIMENTAL CONDITIONS.

Any block of material under the conditions of these experiments, that is, placed in a closed box under load and compressed from end to end, is subject to strains, to which it accommodates itself by that deformation which meets the least resistance. The active force is applied by the forward movement of the piston; the resistances are the firm walls of the box and the downward pressure of the load; only the latter can yield, and therefore the block tends to rise, lifting the weight. The first result of pressure is usually a reduction of volume; but when the block has a minimum volume under the load it must further yield to the sufficient compressing forces by change of form. This change may occur in one of three ways, according to the manner in which the pressure is transmitted through the block.

If the mass be semifluid or plastic the pressure will be transmitted equally in all directions; the block will shorten and correspondingly thicken. Under equally distributed load the form of equilibrium will present an even surface; under unequally distributed load the form of equilibrium will present an uneven surface, rising higher where the load is less. When pushed from one end the block assumes a form of equilibrium only after the lapse of an interval of time which is inversely proportioned to the degree of plasticity; the surface of a uniformly loaded plastic mass may therefore present temporary wave-like inequalities due to the compressing impulses and the rate of plastic flow in the mass. Whether stratified or massive, the sufficiently plastic block will adapt itself solely to the form determined by external forces, uninfluenced by its internal structure, but the strata may register the direction of flow. And this flow may take place by a more or less general but confused rearrangement of the particles of the mass, or by concentration of the movement along definite planes, which are then so related to each other that the mass is divided into bodies of the simplest forms and least number that will satisfy the conditions of the altered volume. This result is one phase of shear-thrusting (Pls. XCIV to XCVI.

If the mass be firm but flexible it will shorten by bending. The resistances involved by bending a free block are the internal resistances to compression on the concave and to extension on the convex side, and under the conditions of experiment the rising bend must also displace the load; this inert weight stiffens the block and modifies the result of flexure. Flexibility varies as the thinness of the mass; therefore a thin block, or one composed of thin layers, will bend more readily, than a massive one; and conversely a thick block, or one composed of thick layers, will transmit the thrust more persistently.

If the mass be rigid, uniform compression will tend to crush it, and if any condition direct the thrust into one plane, or if any plane of weakness exist in the mass in the line of thrust, the block will be sheared along that plane and shortened by the overthrust of one part upon another. It has been shown by Cadell's experiments that the resultant of the compressing force and the vertical direction of easiest movement is an inclined thrust which will shear a sufficiently rigid, flat mass.

The shear-thrusts obtained by Cadell in hard, brittle materials without load and those obtained in highly plastic material under load are very similar. In any process of deformation of strata there are three forces which influence the result; viscosity or internal friction, static pressure or load and the disturbing strain. In order that deformation shall take place, the last must be greater than the other two. Then three phases are determined by the relations of viscosity and load. If viscosity be relatively great fracture results, followed by thrusting on the planes of weakness. If viscosity and load are approximately balanced the form changes by flexure. If viscosity is relatively small, the result is flow, which may take the form of shearing.

In these experiments plastic and flexible masses have been combined; let us examine them separately in behavior with a view of ascertaining how they transmitted the thrust of compression.

BEHAVIOR OF THE VERY SOFT BEDS.

The softest materials used in the experiments resembled butter in consistency, but the base of most of the models was less plastic and retained its form under their weight; it was hard under pressure of a thumb, but warmed by the hand it was easily modeled. When in the box, loaded with a pressure of two to five pounds to the square inch, this material slowly swelled out at the sides; and when compressed from one end it flowed into open crevices. In an early experiment, when a plate glass front of the box had been cracked in many directions and braced with boards that the trial might continue, this substance escaped in sheets thinner than tissue paper through fine cracks; and these very thin sheets stood straight out from the glass to the height of half an inch. Thus this material transmitted pressure in all directions and penetrated into every space of less resistance. Under the conditions of the experiments and the load imposed it behaved like a plastic body, and when all other escape was closed to it, the base yielded to the advance of the piston by somewhere raising the strata and load. The viscosity of the substance was low.

BEHAVIOR OF THE VERY HARD BEDS.

The stratified series in these experiments consisted in many cases of a mixture of equal parts, by weight, of plaster and wax. This material was hard and granular; it could be shaved with a knife and dented by

a dull blow, but it broke under a quick shock. Under load, submitted to compression from one end, it transmitted the thrust through its mass to the farther end; this is evident from the fact that the beds were frequently upset or folded near the resistance beyond the central section of unchanged flat layers. This material did not swell laterally into the space open on the sides, nor did it measureably thicken under direct thrust; nevertheless there was some change of form before flexure took place. This is best shown by the structure of a sheet of tissue paper taken from between horizontal strata at the close of an experiment. (See Pl. LXVII.) In casting some early piles,. oiled tissue paper was placed over each layer after it cooled and the next was poured upon this paper. The structure illustrated was common to all the sheets of paper after compression, but it was not in all cases equally developed. It consists of two sets of lines, those across the direction of thrust being composed of minute wrinkles, those parallel to the thrust being splits in the paper. The wrinkles are not strictly at right angles to the compression; they tend rather to define irregular rounded spaces whose longer axis is across the beds. The splits in the paper express the amount of lateral expansion, but the open cracks in the paper do not correspond to cracks in the beds; the material spread slightly but did not split. Since lateral and vertical expansion were so small a part of the change of form, while, as all the experiments show, bending was a principal result of compression, it is apparent that the piles of strata answer to the conditions of firm and flexible materials. The viscosity and the pressure due to load were approximately balanced.

It has been stated that the thrust was transmitted through the piles to the far end, and this was true of an early stage of each experiment; but it was not to the same extent true of their later stages. The pressure acted longitudinally through the beds, and when they had been bent from a horizontal attitude part of the thrust was deflected upward or downward by them. This is most clearly illustrated by Pl. LXXVI, in which the peak of the anticline was carried up on the broken end of the thick bed until the strata became vertical; and it is also to be traced through the successive stages of other experiments. That portion of the thrust deflected by inclined strata is thus proved to be important, but it is evident from inspection of the section beyond the fold that only a part of the pressure is diverted, and in many cases the greater effect of compression is the result of direct horizontal thrust. The transmission of pressure through a folding stratified mass may be stated as follows: So long as the stratification is parallel to the original direction of pressure, the force is transmitted as a whole and tends to reduce the volume of the mass; when the strata are inclined to the direction of pressure the thrust is resolved into two components, the one parallel to the bedding, the other perpendicular to it; the former produces movement when it overcomes the friction on bedding planes, the viscosity of the strata and any opposing force, as

that of load; the latter becomes active when it can cause some part of the resisting mass to move. This law proved to have an unexpected importance in its influence upon the location of folds.

DEVELOPMENT OF FOLDS AND LAW OF COMPETENT STRUCTURE.

If a strip of bristol board, lying on a table, be pressed from end to end, it will bow upward in a simple curve, the arc of longest possible chord and of least curvature. This is the form of least resistance, that which produces the minimum strains of compression and extension in the board. If a strip of tissue paper is pressed in the same way it will wrinkle irregularly. It differs from the bristol board in that it is not competent to sustain its own weight and is not so homogeneous in texture.

When these experiments were begun it was supposed that the hard strata would bow according to the law which governs the bristol board; it was thought that they would bend over the longest possible chord with the minimum curvature, and that the crown of the curve would be near the middle of the entire length; it was inferred that the distribution of load would modify this result; the hypothesis demanded that under uniform load a simple arch should rise in the middle of the block, and under unequal load the rise should occur where the weight was smallest. This hypothesis was not confirmed; in one experiment the entire absence of load over a central section determined the position of the rise, but the inequality of loading was in this case extreme, and in many other trials the uniformly distributed weight permitted the rise of an initial anticline near the force, an anticline which predominated until it was closed. Hence it was evident that some condition not foreseen exercised a controlling influence upon the locus of flexure. When in the earliest experiments this conclusion appeared, the control was attributed to external friction; but the effect continued after this supposed cause was removed. The importance of internal friction between the beds, forced in bending to move on one another, was next considered; but no adequate explanation could be founded on this, since the adjustment to bending is a local movement dependent upon the thrust from the concave toward the convex curve and is no more difficult in the middle than near the ends of the strata. The rate of compression was next studied. A very slow advance of the piston might create a pressure which, acting uniformly on the entire mass, would cause deformation at the weakest point; a more rapid advance might produce movement near the piston before the thrust could be transmitted to the further end. There is no doubt that these may be valid considerations, but they do not explain the local development of folds in these experiments, as the forward movement of the piston was always very steady at the slow rate of about one inch in five minutes. The fact that the models themselves, in early stages of compression, exhibit quite as much deformation at the farther end as

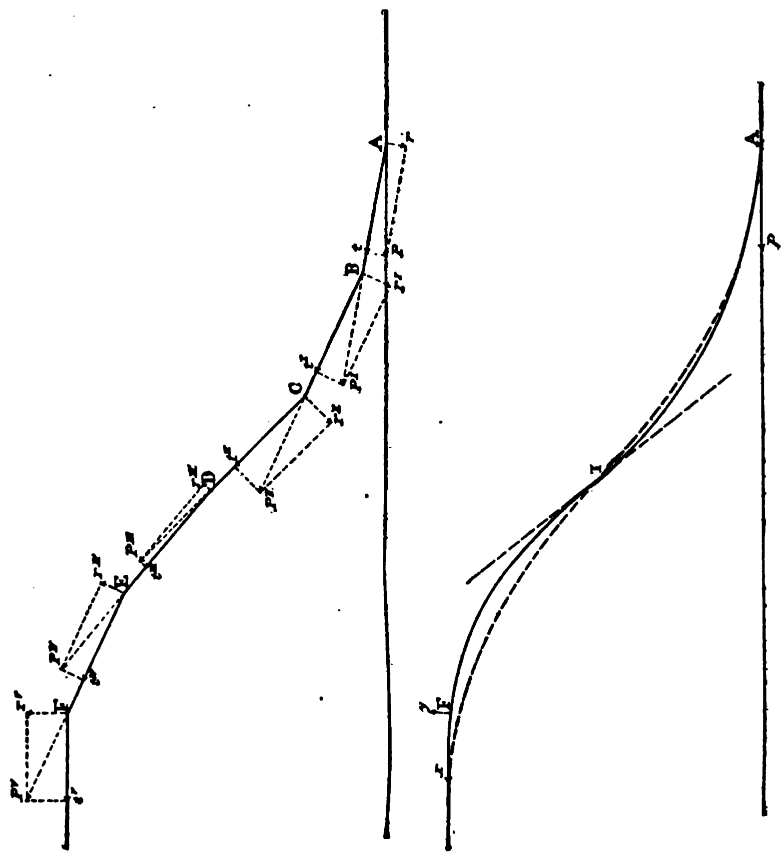


FIG. 17.—Transmission of forces.

at the piston, is the best proof that during the early stages the force was transmitted throughout their length; and the allied fact that in later stages deformation went on principally near the applied force, suggested that the deviation of the strata from the line of thrust was accompanied by deflection of the thrust itself from the direct line. This law has already been stated, but its influence in determining folds was not appreciated until many experiments had been made. Study of numerous models showed that slight dips arose in the supposed horizontal strata before compression, either through irregularities in the casting, or at an early stage of compression through lift of the piston with the ends of the beds in contact with it, or through swelling of the plastic base beneath the flexible layers. The conclusion reached through the experiments was that, when a firm but flexible stratum transmits pressure, it tends to yield by bending along any line, where there is a slight change of dip, and this deviation may be due to initial uplift or depression; the fold is further developed by that component of the thrust which is diverted by the inclined strata.

In order to test this deduction in relation to the experiments and under the conditions they present, several models were arranged in which the initial dip was assumed at different distances from the applied force, and the law was sustained by the results obtained. In Pls. LXXIX to LXXXVI and others, one or more anticlines correspond with the position of assumed changes of dip. The models, Pls. LXXXIII and LXXXIV, are peculiarly interesting, since they are identical in stratigraphy and materials, but differ in resulting structure in a manner wholly dependent on the assumed dips. In one the dip at 6 inches from the applied force determined an anticline, but in the other the two points of change of dip proved effective—first, in proportion to the amount of change; second, in the order of their distance from the applied force.

The models LXXXIV, LXXXV and LXXXVI were identical in the arrangement of layers, but they differed in the nature of the materials; the layers forming the first were hard, the next softer, and the last softest. Comparison of results shows that under the same load the initial dip was important precisely in proportion to the firmness, to the rigidity of the materials. Where the thrust produced plastic flow, inclination developed in consequence of change of form under pressure, and these controlled deformation, while assumed dips exerted a subordinate influence.

For discussion of the effect of forces thus localized and directed, we may consider a case of a firm layer which changes its dip at A and B. (Fig. 17.) The compression $A\ P$ will be resolved at A into Ar and At. The tangential component At is represented by $P\ P'$, and is resolved into Br' and Bt', and so on at each angle of the broken curve from A to F. The components r, r', r'', etc., are the forces tending to deform the firm layer at A, B, C, etc., respectively; they are opposed

by the load if directed upward; if directed downward, they are aided by it; in every case their direction is toward the outer side of the bend. If the bend be a curve instead of a sharp angle, each minute element of the curve will constitute a direction of thrust, and each point of change from one element to another will correspond to A, B, etc. Thus the thrust transmitted by a curved stratum of firm but flexible character is continuously resolved into components tangential and perpendicular to the curve, and the latter acting toward the convex side tend continuously to increase the curvature; we may call these radial components. The tangential thrust grows steadily smaller and finally fades out. Applying this analysis to a compound curve whose point of inflection is I, we have certain radial components tending downward toward synclinal sinking, and others tending upward toward anticlinal rise. The synclinal forces are aided by gravity and opposed by the viscosity of the mass confined beneath the thrusting layer; the anticlinal forces are opposed by gravity and the inflexibility of any superincumbent mass. Folding can result from these opposing forces only when the radial components of compression have sufficient power: (*a*) to bend the thrusting layer, and (*b*) downward, to overcome the viscosity of the underlying, or, upward, to raise the weight of the overlying mass; and when the thrusting layer is firm enough to transmit the effective force.

If we describe the sufficiently firm stratum by the word competent, we may formulate the law of anticlinal development, as deduced from these experiments, as follows: In strata under load an anticline arises along a line of initial dip, when a thrust, sufficiently powerful to raise the load, is transmitted by a competent stratum. The resulting anticline supports the load as an arch, and being adequate to that duty it may be called a competent structure. From the conditions of the case it follows that none other than a competent structure can develop by bending. If the thrust be not powerful enough to raise the load there will be no uplift; or if the layers be so plastic that they yield to the thrust by swelling, then the principal result of deformation is change of form other than by simple flexure, and it assumes some phase of flowing. This is incompetent structure.

CONSEQUENCES OF THE LAW OF COMPETENT STRUCTURE.

(a) *Folding redistributes load.*—In these experiments before compression the layers bore the weight of shot placed upon them, and it was in most cases evenly distributed. During compression competent structures developed and lifted part or all of the load over the span of the arch. Within that span the lower layers then bore less load, frequently none at all, and, as the total load remained unchanged, the springing lines of the arch received correspondingly greater weight. The evidence of this transfer of load is twofold: first, the actual cavities within the developing anticlines, and, second, the swelling of the

FOLDED SHALE.

From Hot Springs, North Carolina.

plastic base which yielded to the greater pressure transmitted to it by the anticlinal limb. This swelling occurred repeatedly just in advance of the first fold and became in each case the locating cause of the second fold. Hence it follows that when layers fold according to the law of competent structure the load which they support is no longer borne as it was before compression. Areas of less and corresponding areas of greater pressure develop.

(b) *The size of a competent anticline is directly as the competency of the effective stratum and inversely as the load.*—To express size we must define the dimension measured, and to give the measurement value we must compare it with some related fact. The dimensions of an anticline or syncline are: longitudinal extent, which we may call the strike length, measured along the axis; at right angles to this, width, measured in cross section from one axis to another of the same kind, and height, measured vertically from one axis to another of different kind. Each distance should be taken between points in the same layer. The strike length of any fold in these experiments was the width of the block, 5½ to 6 inches, and they furnish no data for discussing the relation of axes along the strike. They present facts in cross section only. When flexure is yet gentle the positions of axes are indefinite, and there may be great latitude in determining them; but when folds have become pronounced their axes are fixed and change their position but little in subsequent deformation. The evidence for this statement may be traced through the successive stages of any of the folds produced in the experiments. Width and height are therefore capable of fairly exact determination, and we may express something by comparing them. They are so related to each other in a developing arch that width decreases as height increases, and their ratio is therefore an indication of the amount of compression. Width can not be less than twice the thickness of the strata involved in the fold, unless compression proceed to squeezing; and height can not equal half the distance between fixed axes measured over the curvature of any bedding plane. This last dimension, the distance from an axis of one kind to another of the same kind measured on the bedding plane over the intermediate arch or trough, is the length of the stratum contained in the fold, which in distinction to strike-length we may call dip-length; and this compared with the width is the measure of the amount of shortening in the passage from a flat to a folded position. The dip-length is the only dimension which, during the competent phase of development, does not change materially, and for this reason it affords the best basis for comparison of different folds, whether in the same series or another. The extent of initial dip or the condition of final stages of folding may modify the apparent dip-length, but for the competent arch dip-length is limited. Let us, then, see how and by what conditions.

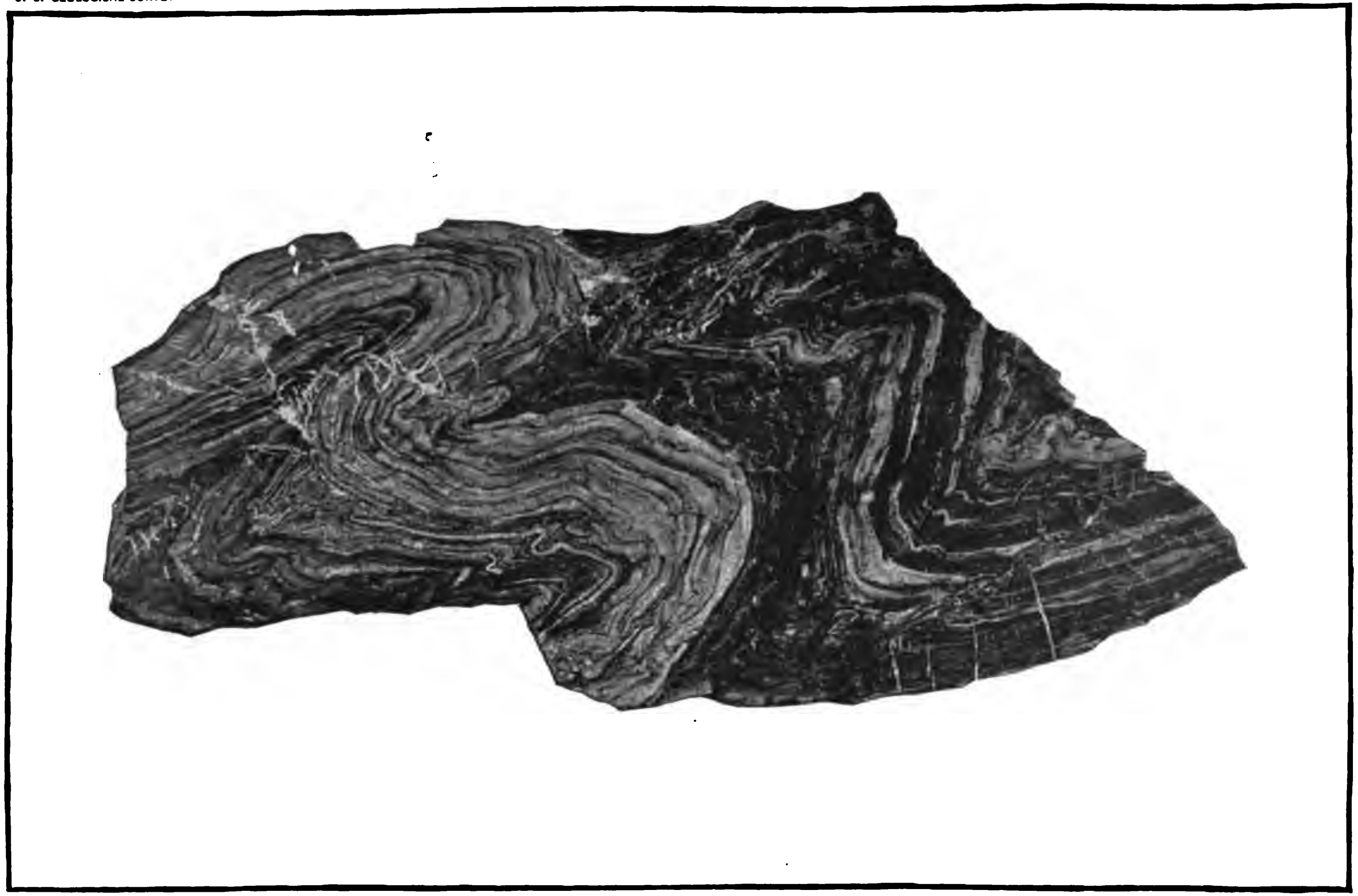
When a firm layer, bent by vertical forces to an initial curve, becomes the competent stratum through which horizontal thrust develops

an anticline, the force which it transmits is resolved into successive tangential and radial components, until the remaining thrust ceases to be effective at a definite distance from the beginning of curvature. We may fairly assume that the force of compression develops gradually until it is sufficient to bend the competent layer and through it to raise the load, and folding will begin as soon as the resistances are overcome. At that instant the competent layer has a less curvature than at any subsequent time; the radial components of the force consequently have their least value at each point, and the tangential thrust of given amount will be effective to a maximum distance. This condition will be aided by the fact that the internal resistances to bending of the competent layer will be least at this moment, and consequently the least force will be exerted in overcoming them. As the curvature increases there grows the proportion of each radial component to its tangential component, and the effective distance for a given thrust diminishes.

From the time the competent layer begins to rise, the growing structure has the character of an arch and sustains the strains existing in a loaded arch as well as the stresses developed in bending. The arch is buttressed on the one side by the inertia of strata beyond the reach of the thrust, and on the other side by the force itself. Its capacity to sustain the load resides in the resistance of the material to crushing, and any excess of force beyond that required to support the load will be absorbed in motion. The resistance of the material depends upon its strength and cross section, that is, upon the coherence and thickness of the competent layer. Hence, for a layer of given material and thickness under a given load, there will be a longest possible span, and, as has just been shown, this span will be attained at an early stage of growth. The length of the strata involved in the arch will not exceed this distance as long as conditions of competency control, and it is therefore the maximum possible dip-length of the convex part of the competent anticline.

The minimum dip-length for a competent layer is determined by its stiffness, for the resistance of the layer to bending must be overcome before the arch can develop, and this exacts the curve of least resistance, the curve of longest possible span. The stiffness is again dependent on the nature and thickness of the layer; thus the minimum, like the maximum, is a function of the competency of the stratum, and we may say: The dip-length of a competent anticline is determined within narrow limits by the coherence and thickness of the effective layer.

The assumption of a constant load is implied in the above statement. If we consider load as variable and the effective layer as constant, a different relation obtains between load and dip-length. A competent structure rises in consequence of the radial components of the compressive force, and these components increase with the degree of curvature. Let us suppose a given stratum transmitting a tangential compression



FOLDED SHALE.

From Hot Springs, North Carolina.

and also bending upward in obedience to vertical forces. At some stage of the bending the radial components of the tangential force will first equal and then exceed the load, and the anticline will thenceforward develop as a competent structure. Now the degree of curvature at which this change will take place will depend upon the amount of load to be raised, and we may state the law: For a given stratum transmitting a given compression the initial curvature demanded for competent development varies directly as the load.

Since the greater the curvature the less the distance to which a given force will be effective, and as this distance is the dip-length, it follows that the greater load demands under given conditions a less dip-length, that is, the dip-length varies inversely as the load.

FIELD OBSERVATIONS BEARING ON COMPETENT STRUCTURE.

Initial dips of deposition and their relation to folds.—Upon a submarine surface the first sediments deposited fill the inequalities, and the later beds are laid successively each upon the even surface of the next preceding. This upper surface presents from the land, seaward, a gently convex profile, the section of the lenticular pile which constantly receives its maximum deposit along a zone near the shore and thins seaward. The area receiving deposits may rise, remain stationary, or subside in relation to sea level. Subsidence is the condition which is essential to the accumulation of great thicknesses of sediment and which is indicated in many districts. It has often been observed that thousands of feet of strata exhibit from bottom to top evidence of deposition in shallow water, and the conclusion is definite that the mass subsided at a rate approximately coincident with that of accumulation. Whether such local depression be attributed to the weight of the accumulating strata or not, it must change the attitude of deep seated beds and develop a trough. Let us call troughs so formed synclines of deposition, and examine the Appalachians for evidence of their existence in that region prior to folding.

The conditions of the problem require datum planes between which measurements may be made, and measures of the intermediate formation or series of formations. If unequal thicknesses of strata are shown to exist between two datum planes, either the upper surface of the strata varied in actual elevation in relation to sea level or the lower datum plane was depressed where the thickness was greater. Among geologic formations a coal bed is, so far as it is well identified, the most reliable horizontal datum, and deposits of slow accumulation like limestone or shale probably formed in nearly level attitude; but coarse mechanical sediments may vary greatly in thickness and then present corresponding irregularities of the upper or lower surface of the formation. If the upper datum plane be a coal bed, then we may be sure that the greater thicknesses occupied depressions in the lower datum plane; and if the lower datum plane be a well-defined limestone hori-

zon we may feel confident that any considerable depressions in its surface are the result of subsidence which took place after the limestone had formed. Measuring in folded strata, we assume that any discovered differences of thickness existed before deformation began, and against this assumption it might in some instances be urged that during folding strata are squeezed and swelled; but this objection is futile when general changes of thickness are proven, and in a special case, like that of the Pottsville conglomerate beneath the Coal-measures, it is incredible that pressure changed the thickness of massive sandstones by hundreds of feet and yet did not affect the accompanying coal beds; yet the Pottsville conglomerate does vary greatly in thickness, and the coal beds show evidence of severe squeezing only in peculiar situations. We may therefore make the following propositions:

(1) If, measured from a definite and formerly level horizon downward, thickness varies, then any lower definite horizon to which the measurements are carried had assumed initial dips before folding took place.

(2) If in a general way greater thickness of strata corresponds with greater depth of synclines, a general relation between synclines of deposition and those of deformation is suggested.

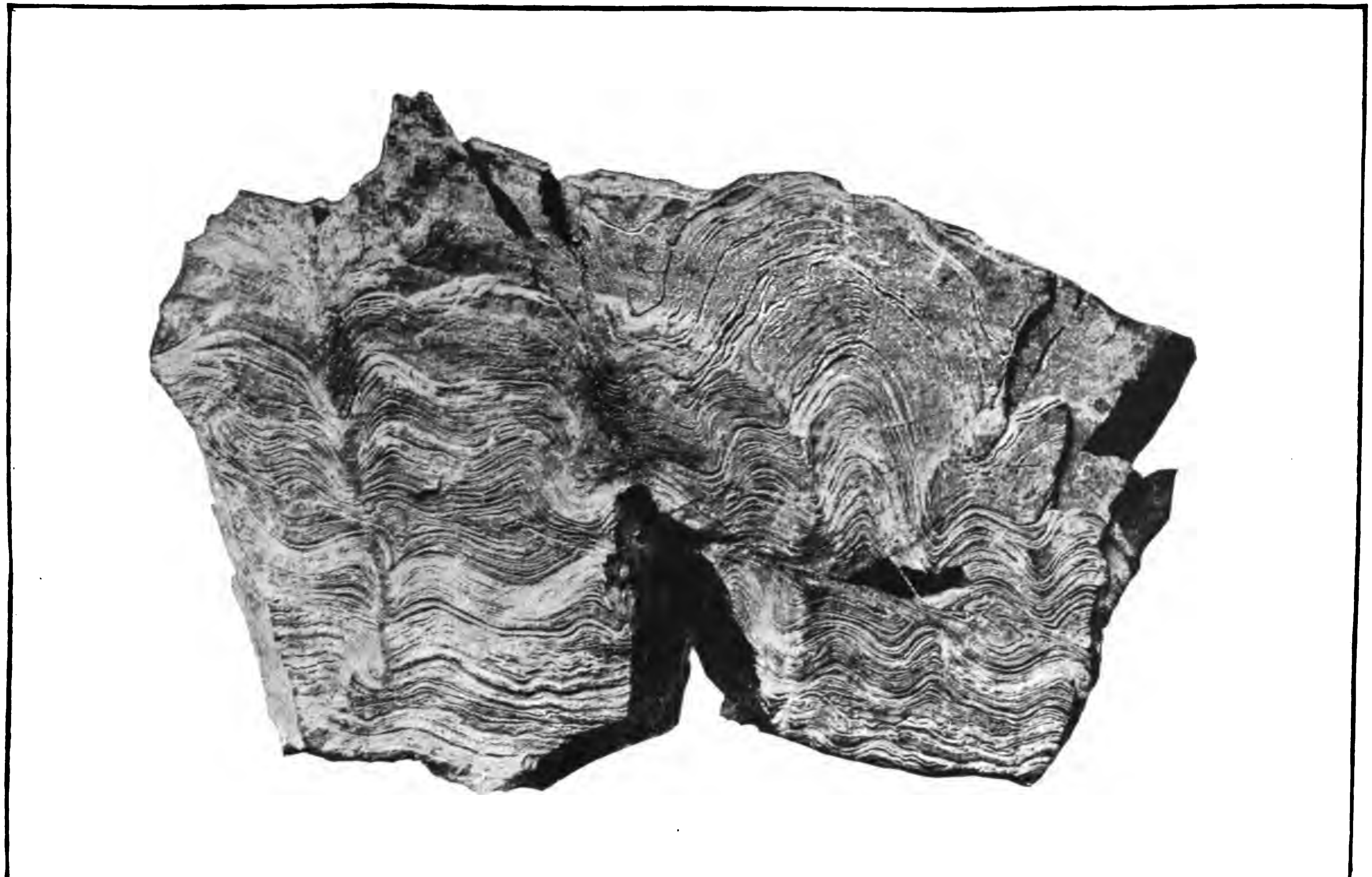
(3) If in specific instances folding and variations of thickness fade out together, the suggested relation is possibly genetic.

(4) If the variations in thickness can be shown to define a lens and the line of greatest thickness of strata corresponds with the synclinal axis the genetic relation may, in the light of experimental results, be considered highly probable; that is, the position of the syncline of deformation was in all probability determined by that of the preexisting syncline of deposition.

(5) If many parallel synclines occur side by side in strata of uniform or gradually changing thickness, their relations are probably independent of initial dips and have been determined by other causes.

There are many synclinoria in the Appalachians which stand out as broad facts of structure demanding explanation, but for few of them are the thicknesses of strata available in sufficient detail for the desired discussion. The Broad-Top basin in Pennsylvania, accessible on all sides down to deep seated strata, and other synclinal areas of Carboniferous and Devonian beds in Virginia, Tennessee, and Georgia deserve study, but I am now able to discuss only three, which are known more or less in detail—the synclinoria of the Massanutten and Bays mountains and the anthracite region.

Massanutten mountain.—The Massanutten lies between the forks of the Shenandoah river—in its northern half, a trough-like valley inclosed by narrow ridges; in its southern half, a single ridge breaking down into knobs toward the end. The syncline contains strata from the Martinsburg shales next above the Shenandoah limestone to the lower Devonian black shales. Northeast and southwest the basin extends beyond the mountain and is represented by an area of Martinsburg



FOLDED LIMESTONE.

From Reading, Pennsylvania.

shale in the middle of the great limestone valley. Its length as a grand structural feature, from its southern tip near Staunton, Virginia, to where it passes into the many folds of central Pennsylvania, is about one hundred and fifty miles; its width through the Massanutten is five to six miles. This long, narrow trough, extending parallel to the shore of the Silurian sea and but a few miles from it, may well correspond with an alongshore belt of maximum deposit and its resulting syncline of deposition. Accurate measures of thickness are not yet available, but the Martinsburg shale in the Massanutten is more than 4,000 feet thick, and on the western edge of the valley, 8 miles farther from shore, it is but 3,000 or less. None of the other formations have been even approximately measured, but this difference would produce a southeastern initial dip in the Shenandoah limestone corresponding in direction with the dip on the western side of the syncline.

Bays mountains.—Three hundred miles southwest of the Massanutten lie the similar Bays mountains of Tennessee; they are narrow, synclinal ridges and peaks, of which the highest, Chimney Top, has an elevation of 3,075 feet. The surrounding valley undulates from 1,200 to 1,500 feet above sea. The strata contained in the syncline are the Sevier shales, resting on the great limestone here called the Knox, and the Clinch sandstone. The formations correspond closely with those of the Massanutten mountain, but the Devonian beds are wanting. The synclinorium, as defined by the Sevier shales, is about 60 miles long from its definite northeastern tip to where it spreads out southwestward and separates into a number of less marked folds. The section through Chimney Top (plate LVII) shows the relation of this synclinorium to the adjacent divisions of the valley on either side; it is a very marked depression in the Knox limestone, which is closely folded to the southeast in the anticlinal belt and rises to a great fault on the northwest. The form of the synclinorium is broader and more irregular than that of the Massanutten, and its detailed structure is more complex; it is, therefore, a less satisfactory illustration of a possible relation between a syncline of deposition and the existing fold. But the initial southeastern dip is again proven by comparison of the thicknesses in the Bays mountains and in the Clinch mountain, 15 miles northwest of it. In the the former the Sevier shales measure 4,000 feet, in the latter but 1,800. They rest upon the Knox; they reach up to the clearly defined Clinch sandstone; the lower surface must have sloped beneath the undisturbed deposits of Clinch to a depth of 2,200 feet deeper in the Bays region than in the Clinch.

Want of facts prevents further analysis of the Massanutten and Bays synclinoria. An initial dip existed in the competent stratum and the present southeastern dip conforms to it. On the southeast, at no great distance, was the shore line, from which initial dips would incline northwestward as the existing dips in the synclinorium now do. The coincidence of a lens of deposits with the present syncline is thus sug-

gested but can not be proved. Nevertheless the magnitude and isolation of the structures suggest a cause beyond the accidents of folding and since a syncline of deposition would have been of coordinate magnitude, and may probably have existed in the particular localities, the hypothesis which refers the position of folds to amounts of deposits is suggested.

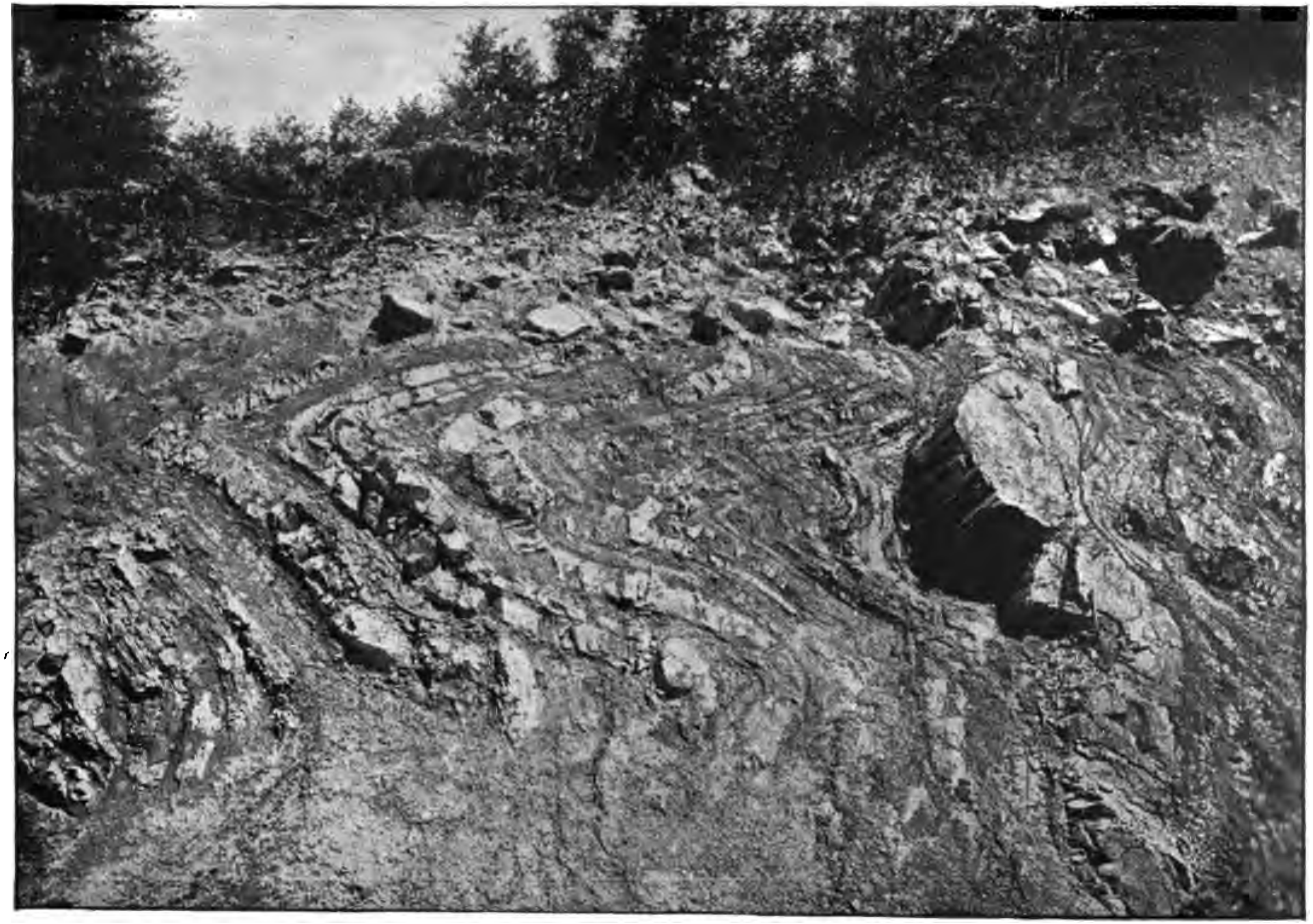
The anthracite basins of Pennsylvania.—In eastern Pennsylvania is a great synclinorium. From the central portion of the state the axes of folds pitch east-northeastward, and before they reach the eastern boundary fade out in flattening dips. Of anticlines, the Nittany, the Berwick, the Selinsgrove, the Georgetown, and the Bloomfield plunge into but do not cross this complex basin; the synclines between these arches all widen and lose their individualities in the undulations of the synclinorium. There is abundant evidence in the details of structure of both the central and eastern parts of the state that the present attitudes of the strata are the results of folding; but in central Pennsylvania the axes rise high and Silurian to lower Devonian strata are exposed; in eastern Pennsylvania the axes sink deep and upper Devonian to Carboniferous strata form the surface. Before folding, was there an initial dip in a competent stratum in this same direction?

To answer this question we require measures of the strata between two datum planes that are recognized over the entire area; as an upper level we may take the top of the Pottsville conglomerate, No. XII, which is so related to coal beds that it is defined within limits of error of one hundred feet or less, and may for this purpose be considered as a formerly level horizon. As a lower datum we may assume the top of the great Cambro-Silurian limestone, No. II, the most competent and most constant stratum of the Paleozic series.

The following sections are taken from the reports of the geological surveys of Pennsylvania:

Formations.	Lycoming county. Andrew Sherwood.	Center county. E. V. D'Invilliers.	Perry county, Susquehanna gap. H. D. Rogers.	Carbon county Lehigh gap. Chas. A. Ashburner.
XII	120	300	600	880
XI	500	150	2. 500	2, 170
X	500	625	2, 000	1, 255
IX	600	2, 650	6, 000	7, 145
VIII	3, 000	6, 134	3, 200	3, 140
VII	50	130	Wanting	340
VI	250	1, 019	Wanting	295
V	2, 500?	1, 040	950	2, 000
IV	1, 375	2, 425	450	460
III	800	1, 011	4, 000	6, 000
	9, 695	15, 484	19, 700	23. 685

The difference in depths of sediment expressed by these sections of strata deposited on the great limestone ranges from 4,000 to 14,000 feet.



FOLDED SANDSTONE AND SHALES, OVERTURNED.

Doe river, Tennessee.

No such variation can be due to inequalities in the top of the Pottsville conglomerate, XII, or of the great limestone, II, or to failure among geologists to identify the identical horizon as the top of the one or the other formation in different districts. The greater thicknesses demonstrate greater depth below a relatively horizental datum, and the plane to which these depths are measured, the top of the Cambro-Silurian limestone, must have had a corresponding initial dip.

Reference to the map (Plate LVI) shows that the sections of greater thicknesses lie to the east and southeast of those of less amount; that is to say, the limestones, II, dipped initially to the east and southeast, and the southeastern dip was the steeper of these two. Parallel to this initial dip now lie the dips of folding; coincident with the more moderate eastward initial dip now pitch the axes of folding. The deepest basins correspond with the depths of the initial syncline; a general relation of position exists between the syncline of deposition and the synclinorium of deformation.

This geographic coincidence is too vague to establish a genetic relation. We can follow the initial dip of the great limestone only from the west and south; on the north and east of the anthracite basins the upper Devonian strata extend horizontally and we can not determine whether the variations in thickness of the older rocks continue or fade out beneath this plateau. But we may continue the comparison of sections of the upper formations into the synclinorium and there trace whatever relation exists between the greater thicknesses and the major details of folding.

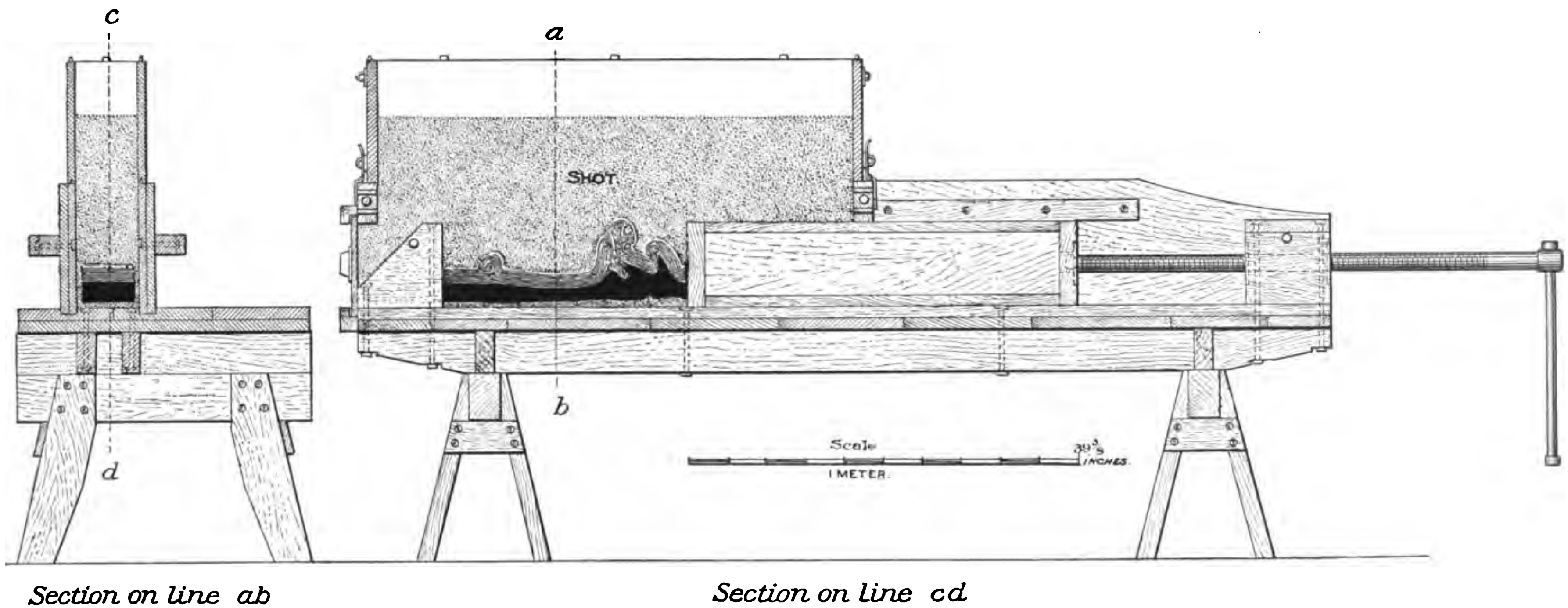
Midway between Center and Carbon counties, between the height of the Nittany arch and the depth of the Pottsville coal basin, the Devonian formations rise repeatedly to the surface from beneath the troughs of the great synclinorium. In a belt taken at right angles to the folds from Lycoming to Lebanon county these deposits exhibit variations in thickness indicated in the following table. For the base of the sections the Lewiston limestone, VI, is taken because it is a well-defined horizon, and it is the lowest bed which appears on every anticline within the belt or near its western edge. Formations IV and V occur in the belt on certain axes but to include them in these sections would too greatly widen the belt; the same is true of the formations above IX.

Formations.	1 North side of Nittany arch. Lycoming county, northwest dip.	2 Western side of Wyoming basin, Columbia county, northwest dip.	3 Northumberland basin, Catawissa, Columbia county, southeast dip.	4 Shamokin basin, Selinsgrove, Northumberland county, southeast dip.	5 Georgetown arch, compiled from both sides, Northumberland county.	6 Wiconisco basin, Perry county, southeast dip.	7 Pottsville basin, Susquehanna gap, northwest dip. H.D. Rogers.
IX	600	5,450	4,300	5,500	5,500	6,000	6,000
VIII	3,000	3,500	5,300	5,250	3,400	5,000	3,200
VII	50	Wanting.	Wanting.	60	50	20	Wanting.
	3,650	8,950	9,600	10,810	8,950	11,020	9,200

There is a relation between these thicknesses of deposit and the major features of folding in the synclinorium. The increase in thickness from north to south corresponds to greater depth of the successive synclines in the same direction and it is evident that the Lewiston limestone conformed to initial dips in a southeastern direction. If we plat the depths of the sections from a horizontal line in their relative positions it appears that the initial dips varied, the descent southeastward was here gentle, there steeper, and between sections 4 and 5 was even interrupted by a northwest initial dip (Pl. LXVIII). And it may be noted that the gentle southeast dips and this northwestern one correspond to anticlines, while the steeper southeast dips underlie synclines of deformation. That is to say, the curves upward and those downward induced in the Lewiston limestone by unequal deposits correspond respectively to the subsequently developed arches and basins. Were the Lewiston limestone, VI, a massive stratum, a controlling member of the series in relation to deformation the conditions demanded by the hypothesis of initial dip and its relation to folding would be complete. But this formation is not massive enough to have controlled deformation in the great mass of sediments of which it is part. We are therefore left to the inference that the initial dips assumed by formation VI were shared by formation II, the great controlling member. As the interval between VI and II varies from 4,000 to 8,000 feet and increases toward the southeast this inference is supported by the general facts, whose details are unknown, and the evidence suggests strongly that the great synclinorium and its major features developed from and in consequence of variable initial dips.

The evidence of available sections does not permit a more conclusive statement; the sections given in the Pennsylvania reports are usually compiled and represent averages for the districts to which they refer. It is therefore probable that more definite determinations made to test the hypothesis under discussion would modify some of the results one way or another although the differences are so great that the general trend of the facts would not be changed. But following the problem still farther into detail we may find additional evidence in the distribution of thicknesses of the upper strata surrounding the distinct basins.

Formations X, XI, and XII encircle the Wyoming, the Shamokin and Mahanoy, and the Pottsville coal basins. These strata are not important in thickness when compared with the deep deposits which they surmount, for they form but $\frac{1}{5}$ to $\frac{1}{3}$ of the total above the great limestone; but from their position we are able to trace their variations along the sides to the ends of the basins and thus we may ascertain what relation their original form of deposit bears to the present troughs. If they were deposited as connected lenses, whose loci of greatest thickness became depths of synclines, we should expect in any stratum to find the smaller thicknesses along the sides of a basin, the greater thickness as we approach the axis, and the maximum at the tip where the



COMPRESSION MACHINE FOR EXPERIMENTS.

axis for that stratum comes to view. An example of this relation appears in the thickness of the lower part of formation VIII, the Hamilton group, which, according to White, is 2,000 feet at Rupert on the northern side of the Northumberland basin, 2,800 at the Susquehanna near the tip, and but 1,200 feet over the Georgetown axis, the second anticline to the south.

The Wyoming basin is a syncline of moderate flexure; the limbs dip most steeply near the western end of the coal field and the trough flattens where the coal measures rise to their eastern limit. The cross section near Wilkes Barre, the broadest part of the basin, shows for the Mammoth coal bed a width of 23,200 feet with a depth below outcrops of 1,580 feet.[1]

The coal basin's rim is composed of the three formations XII, XI, and X, and these with formation IX completely surround it, affording an excellent opportunity to compare the thicknesses of each at different points. The measurements given in the Pennsylvania reports are platted in the map (Plate LVI).

No. XII is unimportant in this region, its thickness being little more than 100 feet and sometimes less; its influence upon structural development could not be greater than that of the sandstones contained in the 1,000 feet of overlaying coal-measures. No. XI is a fine sandstone near the eastern end of the basin, and changes to a mass of red shale toward the southwest; from a thickness of 75 feet north of Scranton it increases in 32 miles to about 1,200 feet at Shickshinny. There the outcrop rounds the tip of the syncline, and from its maximum thickness in this basin the formation thins toward the east. Along the northern edge from north of Scranton to West Nanticoke the rate of thickening is 15 feet per mile; this is in a direction nearly parallel to the synclinal axis. From West Nanticoke to Shickshinny the rate is 100 feet to the mile; this is rapidly approaching the axis. From Shickshinny eastward to Solomon gap receding from the axis the rate of thinning is 50 feet per mile (using Rogers's thickness at Solomon gap) and thence eastward to Cobb gap, parallel to the axis, it is but 8 feet per mile. Taking these measurement by themselves we may reasonably infer the existence of a lens of No. XI, a lens thickest along the line of the synclinal axis. Moreover, the dips of the syncline are steepest where the rate of thickening is greatest and the fold dies out in flat strata where formation XI becomes so thin that its lenticular form, if it exists, can not be influential.

Beneath No. XI lie the massive sandstones of No. X, with quite a uniform thickness of 600 feet. At the Susquehanna gap, on the north of the basin, White gives the formation but 300 feet, with 325 feet of transition beds to the top of No. IX; and on the south at Cobb gap he distinguished at least 400 feet with 375 feet of transition beds, while Rogers states the thickness at but 310 feet. These differences

[1] Ashburner, Second Geol. Survey of Pa. Ann. Report, 1885, p. 285.

evidently indicate that the two geologists have not agreed in dividing the column of strata, but they are not important in this discussion. No. X is massive and under the superincumbent load of 1,200 to 2,000 feet of strata is a very competent bed. Deflected by the unequal deposits of XI it formed a syncline of deposition and, as has just been shown, the characteristics of that syncline are apparent in an exaggerated degree in the present syncline of deformation. The western end of the basin was the region of greater subsidence and is the scene of sharper folding. The eastern end of the basin was an area of very moderate and uniform deposition, and it is there that the trough flattens out.

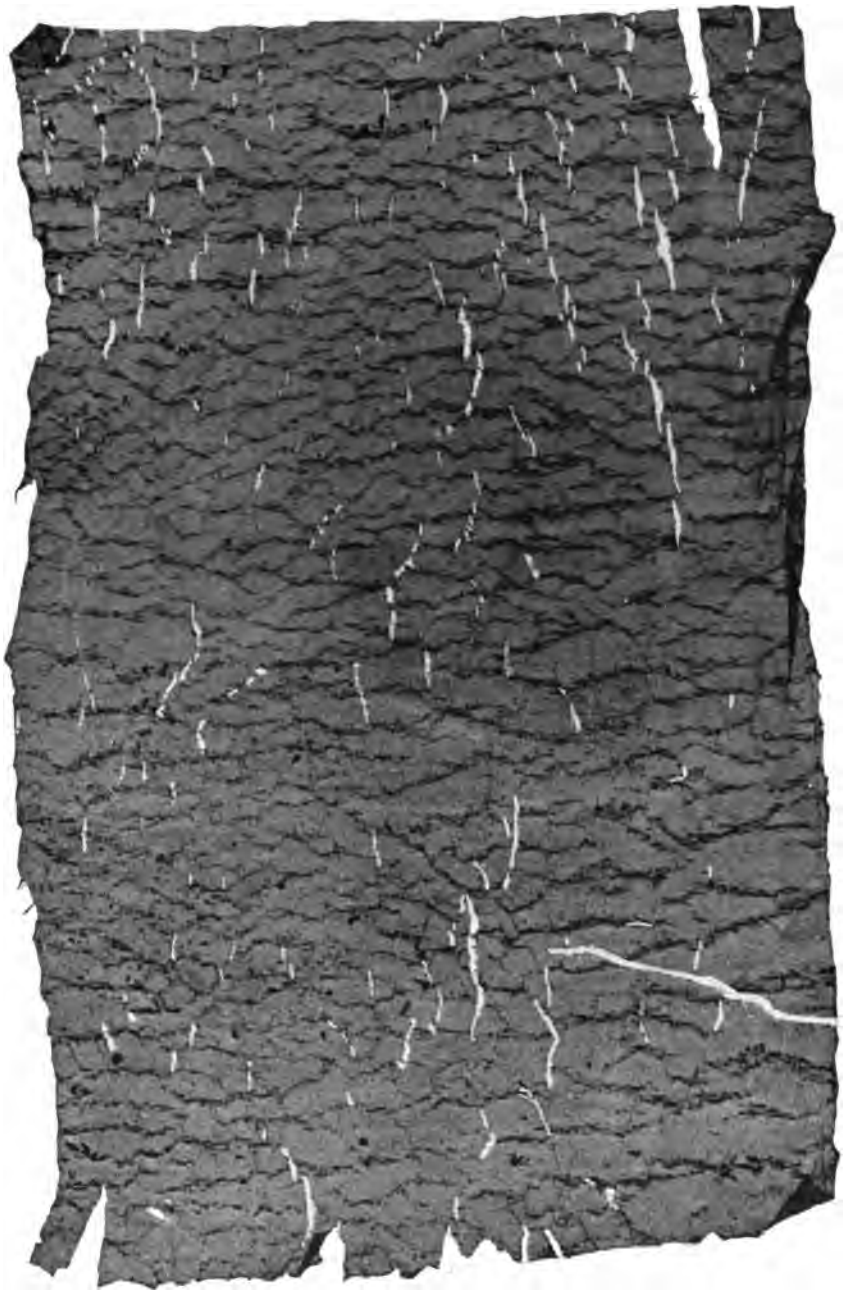
The coincidence is complete, but it may be claimed that it is only a coincidence. The Mauch Chunk shale, XI, thickens from the north to south and west. From Shickshinny where it is 1,200 feet thick it rose over the Montour anticline and where it next appears north of the middle coal basins it is 2,000 to 2,500 feet thick. The rate of thickening between these outcrops is 75 to 100 feet per mile, and it is possible that the occurrence of the maximum thickness in the Wyoming basin on the synclinal axis is an accident of the western position of that outcrop. This doubt can be laid only by more numerous measures along the outcrops of XI or by a bore-hole near the middle of the Wyoming basin.

The Wyoming basin, just discussed, is a somewhat isolated feature of the great Anthracite synclinorium. To the south of it rises the Montour arch, which flattens in its southeastern dip, and the plateau thus formed by formations X, XI, and XII bears the shallow Eastern Middle coal basins. The western edge of this plateau winds like an S around the Northumberland syncline and the rising axis of Selinsgrove, and thence the strata descend southeastward beneath the deeper Western Middle and Shamokin coal basins. From these they rise over the gentle roll of the Georgetown anticline until No. XI appears at the surface and then they plunge into the still greater depths of the Pottsville basin.

The form and relative altitudes of the coal basins among themselves may be inferred from the following figures given by Ashburner:[1]

For the Mammoth bed.	Northern field, Wyoming basin.	Eastern Middle field, Hazleton basin.	Western Middle field, Mahanoy basin.	Southern field, Panther Creek basin near Tamaqua.
	Feet.	*Feet.*	*Feet.*	*Feet.*
Width between outcrops	23,300	3,800	3,050	5,700
Depth below outcrop	1,580	815	1,400	2,275
Bottom of basin in relation to sea level	− 800	+ 850	− 150	− 1,000

[1] Second Geol. Survey of Pa. Ann. Report, 1885, pp. 285–286.



SQUEEZED TISSUE PAPER.

From these figures it appears that the Mammoth coal bed in the bottom of the Hazelton basin lies respectively 1,650, 950, and 1,850 feet above its greatest depth in the Wyoming, Mahanoy, and Panther creek basins. That is to say, the Eastern Middle field has an anticlinal elevation above the other basins.

These differences of elevation, determined on a once level and well-identified coal bed, are the result of rise and subsidence during folding. The question here asked is whether less marked but corresponding undulations existed in buried strata before folding.

Facts of thickness of the formations up to IX have already been cited to show that the great limestone possessed initial dips that in a general way corresponded to the basins of the great synclinorium. To these may be added the available facts concerning X, XI, and XII. Along the northern edge of the Middle coal basins on the limb of the anticline the combined thickness of X and XI is about 3,000 feet (White); at Pottsville, on the south side of the deepest basin, it is about 4,700 (Rogers). Lack of definite observations around the rim of the synclinorium prevents closer analysis of the changes of thickness in these strata, but the general fact agrees with what has been previously stated. For the distribution of formation XII, the Pottsville conglomerate, we have some very exact data given by Ashburner in the reports and maps on the Anthracite fields. In order to measure from a definite datum downward, the sandstones above the conglomerate to the bottom of the Mammoth bed may be included, and the formation of the great coal bed upon this surface is conclusive evidence that it was then a level plane. From the base of the Mammoth bed to the top of XI the thicknesses are: In the Hazelton basin, 470; in the Mahanoy basin, 850–1,200; and in the Pottsville basin at Tamaqua, 900–1,700. Again, there is coincidence of greater and greatest thickness of strata with deeper and deepest syncline. But the relation may be more closely traced.

Ashburner in his detailed reports on the Panther creek and Mahanoy basins gives definite measurements of the strata between the Mammoth coal bed and the top of No. XI. The thickness between the definitely determined top and bottom of this series varies from 900 to 1,700 feet, and the differences are due to changes in No. XII, changes which Ashburner attributes to local currents. He says:[1] "This great thickening and thinning of this group of strata in comparatively short distances, between points which were probably nearly equidistant from the source of the sediments composing the rocks, is most probably accounted for by the existence of local currents at the time deposition took place."

On Plate LXIX are two diagrams compiled from the data contained in the Grand Atlas of the Anthracite fields. These show in plan the distance of each given thickness from the nearest synclinal axis, meas-

[1] Second Geol. Survey Pa. Ann. Rep. 1885, p. 295.

ured on Ashburner's sections on the surface of No. XI. In the Panther creek basin note that the location of the measurement is near the point of the axis at Hacklebarney, section 1; diverges from it as far as Nesquehoning, section 5; and is equidistant from the axis thence to Tamaqua in a direction down the pitch of the deepening syncline. Corresponding with these changes in relative position the thickness, measured or estimated from detailed cross sections, grows less from Hacklebarney to Nesquehoning and gains thence to Tamaqua. This is the relation of thickness to position which should exist if the variations define a lenticular deposit whose longer axis and greater depths correspond with the synclinal axis and its descending pitch. Such a lens as this would be produced alongshore and would thin away offshore as does No. XII from 1,200 feet at Tamaqua, in the Pottsville basin, to 100 feet in the Wyoming basin. A similar but less complete series of measurements is given for the Mahanoy basin, and the variations hold a similar relation of position to the axis of the syncline.

Thus it has been shown (1) that the great anthracite synclinorium corresponds in general position with an area of initial dips to which the massive limestone member conformed; (2) that in general depth and in major details of structure the folding corresponds with depth and undulation of the initial dips; (3) that details of character of individual basins are so related to variations in thickness of one or more members of the folded series as to indicate the coincidence of a lenticular deposit with the area of the basin. All of these may be summed up in the single statement that the facts of thickness and structure are so related as to indicate strongly that the synclinorium and its individual basins are developed features of a preexisting synclinorium of deposition.

The inferences and conclusion from the facts of the Massanutten and Bays mountains seem perhaps more reasonable after the detailed result brought out for the anthracite region; and to students of the Appalachians other extended synclines will suggest themselves, which may trace back their development to conditions of deposition, to original conditions. I shall hereafter use the term original fold to designate structures which owe their development to unequal deposition.

But there are folded areas in which many flexures lie parallel and so close together that it is unreasonable to assume that the closely related structures developed each from a distinct original syncline. A typical instance occurs in the central section of the Alleghanies in Pennsylvania, the section between Harrisburg and Bellefonte. The major features of this belt may be traced to original folds of the anthracite synclinorium and perhaps of the Broad Top basin, but not so the successive undulations of the strata. An explanation of this structure must account for that action of the compressing forces which would cause open folds to develop, one beyond another, without closing any of them. The open fold is the necessary antecedent of the closed, but

even with continued shortening the closed fold is not the necessary consequent of the open. The explanation may be found in the growth of competent structures, but it is necessary first to determine their existence in nature.

Competent anticlines in nature.—In experimental work the first suggestion of an arch competent to bear the overlying load and develop under it into an anticline was received from the growth of open tunnels within the rising folds. In nature this evidence can rarely if ever be observed. The growth of an anticline is so gradual, the friction between rock beds is so important a factor, the balance of pressures in the earth's mass is so steadily adjusted, that no extensive opening between strata is possible. But the development of an opening is the extreme result of lifting the load; it must be preceded by a tendency toward an opening which may be almost equaled by the tendency of less competent strata to rise into the hollow of the arch.

In experimental results the later phase of a competent anticline almost always had a carinate form; the tunnel was narrowed until its sides were brought into contact. It is conceivable that the same result might ensue by a gradual rolling up of the competent bed upon its own vertical or overturned lower surface in such manner that no tunnel ever formed. But whatever the mode of growth, the formation of a carinate anticline must be accompanied by a lifting of the overlying strata, and it is therefore direct evidence of competent development. It follows that the occurrence of carinate anticlines in nature (and they are not uncommon in closely folded regions) is proof of the control of the law of competent structures in those instances. Plates LXX and LXXI are photographs of one such carinate fold, folded up into a steep dip on underlying beds. In both cases the strata are thin-bedded limestones and shales; the keel has a height of about 6 feet. A still more interesting structure is that exposed by the Staunton shaft and slopes in the Wyoming coal basin (Pl. LXXII).

Instances of the exposure of larger carinate folds in such manner that their complete structure is visible are not known to me, but the keel is a feature which is recognized as the isocline and is a characteristic of isoclinal and fan-shaped folds. These occur on a large scale and demonstrate the influence of competent development in structures of greater magnitude. The growth of a keel is the result of the superposition of a competent layer upon an incompetent one, with a plane of relatively easy movement between them, and this is a condition which, while it modifies the result, does not control the action of the force. Hence we may reasonably infer that carinate folds are not the only ones which develop as competent structures; others, whether open or closed folds, probably obeyed the same law of deformation and may bear witness to it in a different manner.

It has been shown for the conditions of the experiments that the load raised upon a competent fold is transferred to the support of the arch. The area within the arch is relieved of weight, and if the effective

force presses from one side, that part of the transferred load which that limb bears is raised by the force, and that part of the load which the other limb bears is supported by the syncline beyond the arch. There is evidence that this relief of pressure on the anticlinal axis, accompanied by upward movement on the one side and excessive pressure on the other limb, is a fact in nature.

In Hoosac mountain, Massachusetts, a conglomerate rests upon the granite from which it is derived. The mountain is of anticlinal structure, overturned toward the east. In the western upright limb the conglomerate has, through shearing, been altered to a gneiss which conforms in foliation to the lamination of the underlying granitoid gneiss; over the crest of the mountain the conglomerate is eroded, but where it appears on the axis near the end of the mountain it is but little altered and its conglomerate character is clearly evident; in the eastern overturned limb the conglomerate is crushed and forms a very finely grained gneiss of different aspect from that on the upright side. The distribution of pressure, as evidenced by the results of dynamic metamorphism and their absence, are strictly in accord with the development of the arch as a competent structure formed by the schists above the conglomerate.

It has been said that conditions of deposition which may account for original folds will not suffice to explain the rhythmic structure apparent in the open folds of the central part of Pennsylvania. The rhythm is probably a result of this redistribution of weight during competent development. If the transferred load have sufficient weight to disturb the balance of its support the syncline will sink, and, sinking, will cause a swelling beyond itself; and the dip thus initiated will grow steeper until the swelling becomes in turn a competent arch. By transfer of load this second anticline will cause an initial dip beyond its further limb, thus bringing about the condition for development of a third anticline; and so on until a more potent condition shall control or till compression ceases. Folds thus caused may be called consequent in distinction to folds that originate in dips of deposition.

A condition important to development of consequent folds is sufficient load upon a competent stratum and yielding support. Let us see, then, if the occurrence of such parallel folding is coextensive with this condition, and so test the hypothesis. In Center county the columnar section from the lowest known limestone of No. II to the Coal-measures of the Alleghany mountain is 21,500 feet;[1] this is a little over 4 miles, and the strata below this column sustained before erosion a pressure of about 24,000 pounds per square inch, which is in excess of the crushing strength at the surface of all but the strongest rocks. The base of the Paleozoic column is usually Cambrian shale or sandstone, but whatever the lowest strata may be in this particular district they would tend to flow from under the passive limb of an arch bearing

[1] Second Geol. Survey, Pa. T. and E. V. D'Invilliers. Map.

such a load per square inch. But if so, was any member of the series competent? The base of the known column is the great limestone, here of extraordinary thickness, 6,000 feet, and of massive character. The load upon its upper surface was about 18,000 pounds per square inch, an amount not in excess of, though nearly equal to, the crushing strength of strong limestones at the surface. It is probable that the limestone would support this load. The question may be answered in the affirmative, and we find the conditions for consequent folds (great load, relatively competent stratum, and yielding base) in the region where such structures are most characteristically developed.

Passing from Pennsylvania into Virginia and West Virginia, strata thin and the rhythmic relation among folds fades out; the distribution of folds in the southern half of the Alleghanies suggests original rather than consequent development, but accurate studies are wanting.

In the southern continuation of this belt, the district of predominant faulting, the parallelism of the great thrusts suggests a consequent relation; but the mass of strata is much thinner than in Pennsylvania. The great limestone is a constant member, 3,500 feet or more thick; the strata above it do not now exceed 7,000 feet, nor do those that are known below it. Thus we are brought to consider the possible case of a consequent dip and fold produced through a competent arch under a moderate load. In the sinking which may result from the transferred load the effective force is the difference between the weight of the undisturbed strata and the still greater pressure beneath the passive limb of the competent anticline, and this difference is a function of the competency of the structure as related to the load rather than of the total thickness of strata raised. That is to say, if a given stratum be competent to raise the whole of a moderate load, the weight acting to produce a consequent fold will be more efficient than that transferred by the same stratum under a greater series of which it is a relatively unimportant member. For in the former case the transferred load will be concentrated by the one stratum, in the latter distributed by the many which go to make up the competent whole. Hence, we may conclude that there is a tendency toward development of consequent folds in advance of any original fold whenever the additional pressure upon the foot of the passive limb is so concentrated as to disturb the equilibrium of its support. In discussing dips of deposition in strata beneath coal-beds, we have inferred that even moderate differences of depth of deposit coincided with corresponding subsidence. Hence we may reason that the disturbance of the isostatic balance which leads to consequent dips and folds is likely to ensue even though the competent stratum sustain but a moderate load, but it may probably be true that the less the load the longer the period of development of consequent dip into consequent fold, and consequently the closer the compression of each fold. From the preceding considerations it would appear that deformation having begun along lines of

initial dips of deposition, consequent folds might be expected to develop in parallel and closely related lines wherever a massive stratum occurred at even moderate depth in the stratified series. The parallelism of folds in the Appalachian province has often been dwelt upon; the continuous limestone stratum, 3,000 to 6,000 feet thick, is a striking fact of the stratigraphy of the entire province. The conditions by theory required and those in fact existing, and the structures by theory suggested and those in nature observed are in perfect agreement. And the assumptions behind the agreement are the hypothesis of competent structure and the sensitive nature of isostatic balance.

For this hypothesis one other test remains. Theoretically there should be a relation between size of anticlines, thickness of competent strata, and the load borne; practically the test is difficult to apply because the competent stratum is seldom a single or constant member of a series and too often the load was a part of the series, now eroded and therefore only to be estimated. And further it is necessary to distinguish between original and consequent folds, since their different modes of development affect their dip-lengths, which we take as a measure of size. The syncline of deposition may be a broad basin before compression begins; when the strata are folded an original anticline arises on one or both sides and at one foot of such an anticline a consequent dip and arch develop. Now the dip-length of the original anticline is half the syncline of deposition plus the length over the competent arch, but the dip-length of the consequent fold is merely the latter. If two or more consequent folds occur together we may expect their dip-lengths to be similar, but when we pass an original anticline and descend into a flexed syncline of deposition, the dip-length should be greater. Thus in the model D, Plate LXXXI, the first fold is an original anticline and the other two are subsequent; the dip-length of the first is 3¼ inches, of the other two 2 and 2½ inches respectively.

With these relations in mind let us turn once more to Pennsylvania and study the sizes of folds through the aid of the excellent sections published by H. D. Rogers[1] and copied in part on Plate LVI. In the analysis of this structure for its relations to stratigraphic thicknesses, certain basins and their adjacent anticlines were shown to be more or less probably original. These named from northwest to southeast were the Nittany arch, Wyoming, Broad Top basins, Montour arch, Northumberland basin, Selinsgrove arch, Shamokin basin, Georgetown arch, Wiconisco basin, Bloomfield arch, Pottsville basin. The dip-lengths of these folds, measured from synclinal axis over the anticline to synclinal axis, vary from 22½ to 48 miles, and the variation depends upon the fold measured, or in different sections of one fold upon the position of the section; for anticlines are limited in strike-lengths and dip-lengths lessen as they die out. This variation is not inconsistent with the hypothesis of competent structure since the dip-length in each case is

[1] Dip-lengths were measured on the original sections as published by Rogers.

CARINATE FOLD IN LIMESTONE AND SHALE.

Coosa shales, Alabama.

the length over the competent arch plus an independent amount measured on the exaggerated dip of the syncline of deposition. But associated with these original folds are those which by their parallelism and close relations among themselves may possibly be consequent; if so, other things being equal, their dip-lengths should be equal among themselves.

In section VI the Nittany arch has a dip length of 35 miles. At its eastern foot is a group of three folds: *a* 9, *b* 9, *c* 9½ miles in dip-length and beyond these follow three others of gentler dips: *d* 6, *e* 5½, *f* 6¾ miles in dip-length. On this section these folds are strictly parallel. In section VII, 21 miles southwest of section VI, the folds are divergent and their relations are changed. The Nittany arch, increased to 48 miles, sinks rapidly to the southwest and disappears; *a* risen to 12 miles in dip-length, becomes the original anticline on the western edge of the Broad Top basin; *b* and *c* have died out; *d* 6½ and *e* 5½ miles, continue as undulations in that basin; *f* has become the original anticline of Kishacoquillas between the Broad Top and Northumberland synclines. Where there is parallelism in section VI there is equality of dip-length in folds of either one of the two groups; where there are divergent folds of probably original type in section VII there is inequality of dip-lengths. The facts fit the hypothetical relations of consequent folds with one exception, the division into two groups of sizes of 9 and 6 miles, which may be a result of the unlike loads borne by the original anticline and lying in the original syncline. But, however the residual fact is to be accounted for, it does not contradict and the other facts in agreement do sustain the hypothesis of consequent folding.

Southeast of the Northumberland basin, section VI crosses only original folds; but section VII shows two groups of parallel axes with approximate equality of dip-lengths in each group. These are: *g* 7¾, *h* 4¾, *i* 4½, *j* 7 miles between Northumberland and Shamokin basins, and *k* 6½, *l* 4½, *m* 6½ miles between the Wiconisco and Pottsville basins. There is a striking symmetry in each of these groups; the greater dip-lengths lie outside along the original folds, the smaller lie within; and among the three smaller ones there is equality, as of consequent folds developed under uniform load by an equally competent stratum. What was here the competent stratum? The measures are, like others previously quoted, taken on the top of formation No. II, but if we consult the graphic sections it is apparent that the folds of No. II and No. IV can not be parallel. No. IV dips more steeply; it rises higher relatively to its synclines; apparently it was itself independently competent, and, composed of 2,400 feet of sandstone and conglomerate, it may well have been. Measuring then over its upper surface we get for these same groups of folds: *g* 7¼, *h* 7½, *i* 6½, *j* 8½, *k* 6½, *l* 6, and *m* 8½ miles. The equality of the folds in the two groups is even more apparent and the necessary inference by the consequent hypothesis is that the load

was uniform over No. IV throughout their areas. Now the second group of k, l, and m is in the strike of the Pottsville basin, a syncline of deposition caused by excessive sediments; where section VII crosses this line of strike the original syncline fades into the anticline of the Cumberland valley, part of the great valley, and, reasoning simply from this fact, we might argue that the inequality of deposition ceased where its effect, the Pottsville basin, dies out. Thus facts of original and of consequent deformation in this locality accord in suggesting the common conclusion of uniform deposition.

In that part of Pennsylvania northwest of the more strongly marked folds the strata undulate gently with dips usually less than 20 degrees. The absence of conspicuous anticlines or synclines suggests on the hypothesis of original folds the absence of marked variations in thickness of strata, and the conditions on the gentle northwestward slopes would seem to have been favorable for consequent folding. From sections II and IX, of Rogers, the measures of dip-lengths show for each section an approximate equality that supports this inference, even though we do not possess the facts which might explain the less dip-lengths of 14 and 19½ miles in the western end of section IX, or the broad relation of shorter dip-lengths in IX than in II.

To sum up for competent structures: From field observations it has been shown that initial dips existed as the result of unequal deposition and their relation to folds of compression is such as would follow if the pressure were transmitted by certain massive beds, called competent. Theoretically, pressure so transmitted should raise arches which would carry up the incumbent load by virtue of their structural strength, and in proof of the existence of such anticlines carinate folds and facts of dynamic metamorphism are cited. The latter result from redistribution of pressures transferred by the competent structure, and the idea is broadened by the suggestion that such transferred load would, like unequal weights of sediments, cause a dip which would develop into a fold parallel to the original one. Herein lies a possible explanation of the extraordinary parallelism of structures in certain districts, and the explanation is tested by applying a law of dip-lengths to the folds supposed to be consequent. The dip-lengths are found to agree with the hypothesis. Thus at each step the logical deduction is confirmed by observed facts, and the law of competent structure is found controlling.

APPALACHIAN THRUSTS.

The district of Appalachian thrusts is 450 miles long, and within it the dominant structural facts are faults which (1) arise and die out in the northwest limb of anticlines characterized by gentle southeast and steep northwest dips; (2) have a fault-dip to the southeast, usually parallel to the gentler dipping limb; (3) are not marked by greatly thinned or schistose strata; (4) in spite of displacements, that sometimes must exceed 5 miles, never bring to the present surface any rock

CARINATE FOLD IN LIMESTONE.

Little river, Chilhowee mountain, Tennessee.

older than Cambrian strata; (6) are wonderfully persistent, the longest reaching 375 miles, and are remarkably parallel among themselves; (7) lie in a zone continuous with that of open folding, but occur in that part of it where the great Devonian sediments certainly, and most of the Carboniferous probably, never were deposited.

From these facts it has been inferred that (1) Appalachian thrusts are a result of peculiar anticlinal development and are produced by a force transmitted through the gentler dipping limb; (2) faulting checked flexure at a stage prior to excessive compression of the anticline; (3) the phenomena are confined to stratified beds and originate in them; (4) the condition which favored faulting rather than continued folding was general over the entire district and the antecedent folds were related to one another in a manner to produce parallelism; (5) the reason for faulting in the southern and folding in the northern half of the continuous zone is to be sought in the differences of stratigraphy between the two districts.

The stratigraphic contrasts are strikingly brought out by a simple statement of the fact that the thickness above the Cambro-Silurian limestone is 23,000 feet in the Pottsville basin, 10,000 feet in southwestern Virginia, and 4,000 feet in Alabama, including in each statement the highest Carboniferous strata known in each district. We know, as the few sections already cited prove, that strata vary greatly in thickness and within short distances. Thus the deposits of the Devonian period vary from 10,000 feet in eastern Pennsylvania to 7,000 in the central part of the State. This thickness they retain southwestward nearly through Virginia and then thin rapidly. Near Big Stone gap they are represented by the single formation, the black shale, 750 to 900 feet thick, and this extends through Tennessee to Alabama and Georgia with a thinness of 30 to 100 feet. Ten thousand feet of sediment represented by 30 feet! The statement is not strictly true since the 30 probably represents only the lower 2,000 of the 10,000 leaving 8,000 unrepresented, but none the less is the fact apparent that the Devonian record was never made in the South, while its bulk in the North is enormous.

There are five stages of the earth's surface in relation to the sea-level and shore, and the completeness of the sedimentary record is determined by them. They are abyssal, thalassic, sublittoral, base level, and continental. To the abysses of the ocean mechanical sediments are scantily transported, and there organic deposits are redissolved; in shallower seas remote from land the sediments consist only of organic ooze; in seas along the shore or of moderate depths the products of erosion and of organic activity accumulate, if land and sea are so conditioned as to provide them; upon land scarcely elevated above sea-level mechanical and chemical erosion both fail, and the adjoining sea, receiving no sediment, makes no record; upon elevated land masses, such as the continents now generally present, erosion is important, the mate-

rials are carried seaward, and the bulk of the record in the sublittoral zone is in proportion to the activity of the agencies on the land. The effect of long-continued degradation is to reduce all height nearly to sea-level, to a base level, and when that stage is reached geologic history is unrecorded until uplift revives the streams of the continent and they go to work again.

To account for the absence of Devonian deposits in the South we are free to choose between three hypotheses: either the Appalachian basin was sunk in an abyss which sediments could not reach, or the mediterranean sea was so remote from land that sediment did not reach it, or the land was degraded to a base-level, and therefore furnished no sediment. Processes which inevitably produce a base-level unless the continental mass is renewed by uplift, had long been in operation, as is proved by Cambrian and Silurian sediments; and the probabilities favor the last theory, which is a legitimate result of known cause, rather than the others, which are pure assumptions without explanation. I have touched upon this difficult problem of stratigraphy, not with the intention of stating a definite conclusion, but to enforce the point that time lapse and sediment bulk are not necessarily proportionate, and we are not free conveniently to assume that erosion has removed strata from areas where they do not now exist.

Such considerations must influence conservative estimates of the amounts to be added to the thicknesses now existing above the great limestone, which are given on the map. (Plate LVIII.) In each case the figure is placed in the syncline containing the measured deposits, and the highest formations included are indicated by the appropriate period color. The coincidence in area of the faulted district with the absence of the mechanical sediments of the Devonian, and the persistency of simple folding where these strata do occur, suggest that they strongly influenced the type of resultant structure. Where they exist the thicknesses above the limestone exceeds 10,000 feet; where they fail, although the column includes Carboniferous beds, this thickness falls below 10,000 feet, and I can find no reason for assuming that deposits should be restored over any part of the faulted district to an extent which would make this total exceed that figure or, in much of the area, add up more than 5,000 feet.

Recalling the threefold character of the sedimentary series, the laminated base and top and massive middle, the preceding facts and inferences suggest a simple hypothesis of faulting: Under the given sedimentary conditions flexure resulted in a series of stepfolds of broad tread and small rise, which developed until further folding became more difficult than the shearing of the short vertical limb; then the fact of shearing permitted the higher step to slide forward upon the one in front of it. Two circumstances in this hypothesis remain unexplained: why stepfolds should form and why folding should become

more difficult than shearing. Let us take them up in the order of their statement.

What I have here called a stepfold is an anticline with one long gently dipping limb, and the other short and vertical or overturned. As stated by Heim, the condition which leads to such unsymmetrical folding is that the one syncline shall be deeper than the other; then the steeper dip is toward the deeper syncline, and toward this side the strata may be overturned. Two modes of development, I conceive, may lead to this difference in depth of adjacent synclines and so to stepfolds; the one original folding, the other consequent. Given a series of strata gently inclined seaward, but elevated so that the shore shall lie along their slope, then, if there are deposits along the shore, they will thicken rapidly seaward to a maximum, and beyond that line thin away more gradually; beneath these a syncline of deposition may develop with unequal dips. Where the older strata pass from their attitude nearest the land to the steeper dip into the syncline, the curve is convex upward, and upon compression must develop into a stepfold—one long limb dipping gently shoreward and one short limb dipping steeply seaward; and from the foot of the step rises the gentler shoreward dip of the syncline. Such is the probable origin of the closed Clinch syncline, in which the sub-Carboniferous Newman limestone is the highest stratum. This formation is elsewhere a compact limestone 600 to 800 feet thick; in this fold it is a very earthy limestone, weathering to a yellow shale, 1,600 to 1,900 feet thick. Beneath it lies the arenaceous Grainger shale, here 900 feet thick, but 15 miles northwest only 420 feet thick. The great increase in thickness over the average of these two formations is evidence of proximity to source of material, to a shore yielding appropriate sediments; and a possible source of such argillaceous detritus and of at least part of the sand is the mass of calcareous Sevier shales in the Bays mountains, capped by the Clinch sandstones, 15 to 25 miles southeast of the deposit.

The idea conveyed in this suggestion that Silurian formations may have furnished sub-Carboniferous sediments contradicts the accepted traditions of Appalachian history. It is the prevailing view that the accumulation of Paleozoic deposits went on without interruption from Cambrian to Carboniferous over the entire province and was closed by a period of deformation of extraordinary activity—a period of such huge mountain growth and enormous degradation that it can be characterized only as a catastrophe. Rather than to crowd events of such magnitude into a brief geologic period, the latest Carboniferous and earliest Trias, a more reasonable view would suggest that deformation began early and was recurrent during the continuance of sedimentation. The suggestion is not without foundation in fact.[1] There is an unconformity between Lower Cambrian and Calciferous, and another at the close of the Trenton, which has not yet been fully described in any publication,

[1] Keith: Read before the Phil. Soc. of Wash., April, 1892.

but is well determined by discordance of strata and basal conglomerates derived from the Knox (Calciferous) limestone. These two unconformities are recognized only along lines of outcrop on the eastern edge of the Appalachian valley; farther west the strata are apparently conformable. The later of the two immediately preceded the deposition of the Sevier shale and no subsequent unconformity has yet been discovered, but this negative does not justify the assumption that none has existed. The zone of discordance may have been eroded. Consider the abrupt passage from horizontal to vertical strata along the edge of the Cumberland plateau, where the deep valleys now existing are but a comparatively late result of continental rise. Were deposits spread upon an even surface of erosion over the plateau and western line of folds they would be conformable to the one and unconformable to the other, and the zone of unconformity would be sharply limited. Should later deformation exaggerate the folding and lift the plane of unconformity, its complete erosion would ensue and there would remain no evidence of it in the surviving and perhaps flexed deposits to the west. Or, were the western edge of the folded Appalachian zone the shore of a sea covering the Mississippi valley, deposits over the Cumberland plateau would be even yet conformable to the Carboniferous, barring erosion, and only the greater thickness contained in some syncline of deposition or conglomerate of Paleozoic rocks would show that the shore lay along the western anticlines of earlier deformation.

The syncline of deposition formed by sediments, lithologically identical with the source from which they are supposed to have been derived, exists in the Clinch trough, and the evidence tends to show that the shore of the sub-Carboniferous sea was probably northwest of the Bays synclinorium. Whether the Silurian strata between that shore and the crystalline continent had been folded during Upper Silurian or Devonian time is not yet determined, but it is quite possible that they were. In any case the Knox limestone had certain initial dips; from beneath the Sevier shales, 4,000 feet thick in the Bays synclinorium, it rose as they thinned to 1,800 feet, and from the line of the supposed shore dipped northwest under the added thickness of 1,600 feet of Newman limestone plus 900 feet of Grainger shale. The hypothesis of step-folding required only unequal northwestern dips, but here the conditions of stratigraphy seem initially to provide the southeastern and also the northwestern. Thus the condition antecedent to faulting, the step-fold, is accounted for by a reasonable interpretation of the facts, and along this probable step-fold of deposition runs one of the greatest of the Appalachian thrusts.

As with certain folds of central Pennsylvania so with the thrusts of Tennessee; the structures are too intimately related and too conspicuously parallel to admit of explanation solely by independent original conditions. But it is clear that a step-fold such as has just been de-

scribed would tend to develop a consequent fold in advance of and parallel to it, which under like conditions should result in a parallel fault. For the original step-fold, raised by a thrust transmitted by the strata, must be competent, and through its shorter limb must transmit part of the lifted weight to the deeper syncline; and the form of the resulting depression which determines the form of the consequent fold will depend on the amount of the weight thus transmitted. For, if great, this weight may sharply deform the immediately subjacent strata, but if moderate, it can only disturb the equilibrium of the relatively inflexible stratum by depressing a long segment and displacing the latently plastic support. This subterranean support, measured by the subsidence of sedimentary deposits, is thought to be lightly though slowly adjustable, and the width of the inclined segment extending from the depths of the original syncline seaward to the crest of the subsequent anticline will be determined as the leverage, which the load requires to overcome the inflexibility of the strata. Hence if the extra load upon the syncline be very great the strata will bend down sharply and the consequent anticline will lie near the foot of the original; but if the load be moderate the strata will be depressed more gently and the axis of the subsequent arch will be farther away. If it be granted that the load on the competent stratum was moderate throughout the faulted district, the long limb of a consequent step-fold may be thus accounted for.

If the preceding analysis of downward deflection be correct, it follows that the anticlinal bend, the knee of the step-fold, will be sharp, and when occurring simultaneously with compression will be equivalent to a joint against which an oblique pressure is exerted. Compression demands that this joint shall bend, and to do so it must determine a second one, an ankle, around which it may swing as a pivot. The first stage of this fold will be a simple competent arch. During its second stage the middle limb of the complete fold is revolved by pressure from opposite directions through the pair composed of the upper and lower limbs, and during this phase the fold transfers the load competently borne and the developing syncline sinks, producing in its turn conditions for a further consequent fold. In the third stage the revolution of the middle limb has been completed and the conditions for fault development are reached.

However future observations and discussion may modify this explanation of the growth of original and consequent step-folds, the fact is that from folds of that type Appalachian thrusts developed, and the conditions of that development remain to be considered. I conceive that there are three possible varieties of thrusts, produced, respectively, by breaking, by shearing, and by erosion.

It is a general principle, stated by Heim, Gilbert and others, that deformation by fracture occurs under moderate load and deformation by flexure under great load. For those who hold the view that the

district of faulting was a district of moderate load on the great limestone, the idea lies close at hand that in bending the massive stratum broke and the plane of fracture became a plane of overthrust. Faults thus determined should intersect the arc of sharper curvature, either anticlinal or synclinal, and the fault dip should be radial to any observed or reconstructed fold.

The possible shear is the result of a short middle limb, which being revolved into a position at right angles to the other two limbs is in the position of a strip athwart two rigid masses, whose thrusts in opposing directions are not fairly opposite. If the thrusts be sufficiently powerful they will pass one another and the middle limb will be sheared if it bear a moderate load, or stretched, as described by Heim, if it be overloaded to the extent of plasticity. The fault dip will then be parallel to the isoclinal structure resulting from an adequate overthrust.

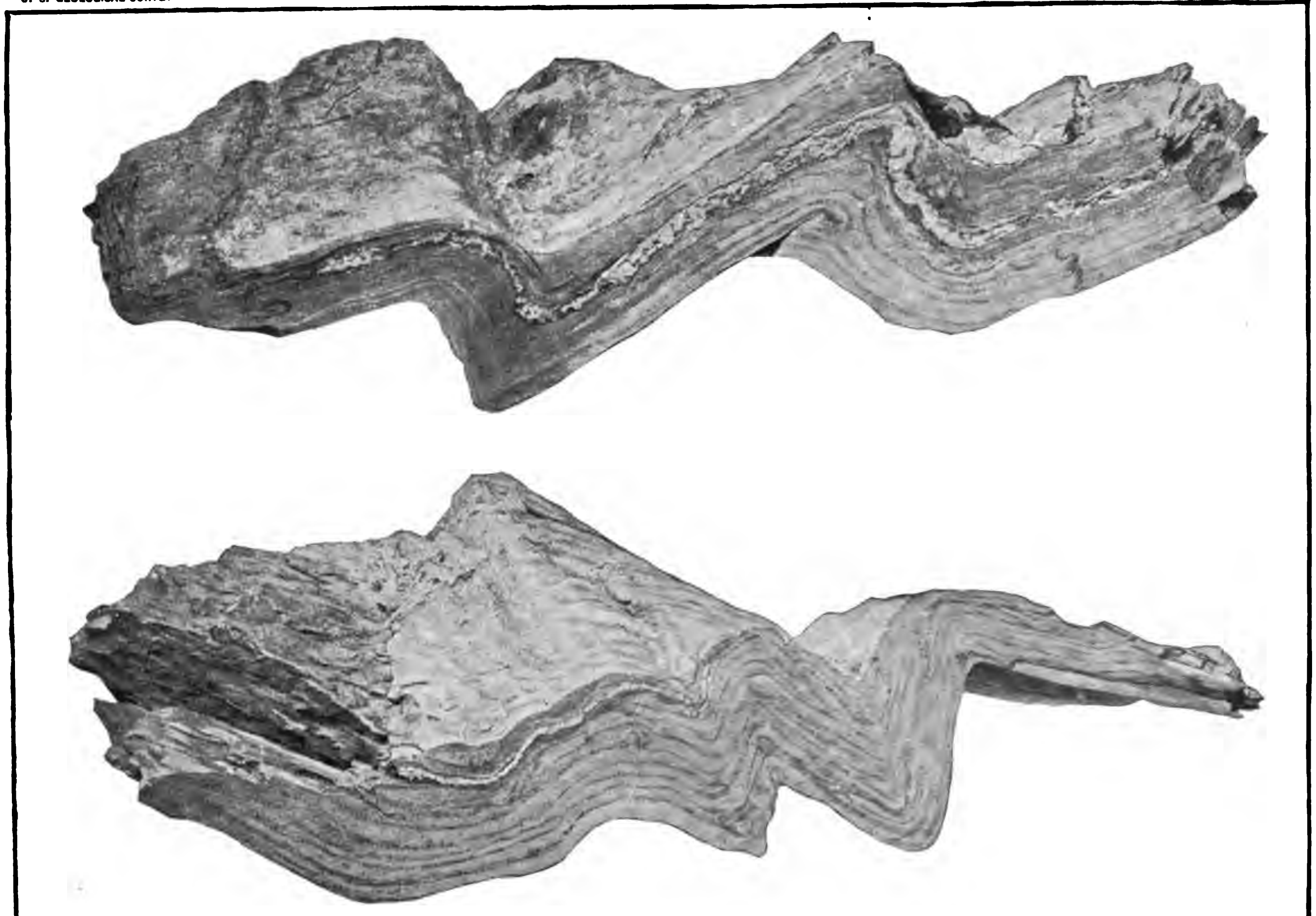
Thus far the discussion of structural development has been continued with tacit disregard for the probable influence of erosion, an assumption which implies that deformation progressed so rapidly as to complete its course before degradation could become effective, or that the structural surface was constantly submarine. Neither implication can be correct. Long time, even geologically speaking, is required for the bending of strata. Force, great, yet barely sufficient to overcome the enormous resistance, acted through ages gradually to accomplish changes of form, which sudden effort, however mighty, could never have produced. Violence might fracture, crush, destroy; steady pressure alone could systematically bend or shear sedimentary masses. Anticlines, then, were long in rising; synclines deepened slowly; and even if we assume that deformation began in a submarine zone, the heights of the anticlines must have risen above sea and been degraded as they grew.

The effect of this upon a step-fold such as has been described must be ultimately to cut off the crown of the competent bed and destroy the resistance opposed to it; further pressure must then produce such overthrust that the base of the rigid stratum will rest upon the surface of erosion and the latest deposited beds in the syncline beyond.

THEORETICAL SUGGESTIONS.

The Appalachian province has afforded illustrations of structure to prove a majority of the conflicting theories of mountain origin. Its broad facts have been appealed to by all who would generalize on the distribution and form of mountain ranges and they have served impartially the dreamer and the student. Accurate descriptions of details and the analysis of the mechanical conditions which governed their development, are essential to a satisfactory consideration of theories as to the cause of compression.

H. D. Rogers, whose descriptive writings of what he saw are unsurpassed in accuracy, but in whose day theories of geology



STEP-FOLD IN SLATE.

assumed development by catastrophies, saw in the undulating folds proof of an "onward billowy movement proceeding from beneath, and not of a folding due simply to some great horizontal or lateral compression."[1] In his opinion, which he shared with his brother, "No system of narrow waves of the strata, however flat, could originate from the most enormous lateral pressure, if unaccompanied by some vertical oscillation, producing parallel lines of easy flexure. Precisely such an alternate movement would ensue if a succession of actual waves on the surface of the subterranean fluid rock rolled in a given direction beneath the bending crust."[2] The idea of a "subterranean fluid rock" set in undulation by the "sudden and explosive escape of gaseous matter" is no longer seriously considered, but Rogers was in touch with truth when he postulated "parallel lines of easily flexure" due to "vertical oscillation." To-day that oscillation is attributed to slow adjustments of balance. On the other hand, those who, like Suess and Heim, find in tangential pressure a sufficient cause for the structure of the Jura and Alps, seek confirmation of their views in the simplicity of Appalachian folds and their evident relation to the shortening of an arc of the earth. Probably nowhere in the world is the action of horizontal pressure apparent on so vast a scale, in such grand grouping of effects without complexity. Had Rogers had the advantage of the studies of the fifty years that have elapsed since his theory was published, he would have grasped the truth more securely and he might have solved those remaining questions, which still cast doubt on the contractional hypothesis.

These doubts have been forcibly stated by two scientists, each of whom proposes a different theory based on the conspicuous fact that areas of great deposition are zones of folding. Mellard Reade makes an argument to prove that contraction of a great circle of the earth by cooling could not produce the observed shortening of the Appalachian and other parallel zones, even were it possible to concentrate it, and then proceeds to show that expansion by heating of these zones alone is sufficient to produce the length by which the folds exceed the width they now occupy:

> Mountain ranges are ridgings up of the earth's crust which take place only in areas of great sedimentation.
>
> The exciting cause of the various horizontal and vertical strains ending in the birth of a mountain range is the rise of the isogeotherms and consequent increase of temperature of the new sedimentaries and that portion of the old crust that they overlie.
>
> This rise of the isogeotherms, the direct result of sedimentation, by a series of reactions described in detail in the body of this work, evidently produces an accumulated temperature much in excess of its normal effect.
>
> The rise of temperature exerts a tendency to expand the new sedimentaries in every direction in proportion to their extent and mass. The tendency to expand

[1] Reports of the Assoc. of Am. Geol. and Nat., 1840, 1841, 1842, p. 508. On the Physical Structure of the Appalachian Chain, H. D. and W. D. Rogers.

[2] Op. cit., p. 512.

horizontally is checked by the mass of the earth's crust bounding the locally heated area. The expanding mass is therefore forced to expend its energies within itself; hence arise those foldings of lengthening strata, repacking of beds, reversed faults, ridging up, and elevatory movements which occur in varied forms, according to the conditions present in each case.[1]

Contraction and expansion are not such widely different effects for any given change of temperature that the expansion of a zone a hundred miles wide could accomplish what contraction of a far greater arc shall fail to do. In that proportion by which the zone is shorter than the arc must the rise in temperature be greater to expand the zone by a given length than the fall in temperature required to contract the arc by the same actual number of miles. Reade's argument seems to me to be either self-destructive or to suggest that cooling of the earth must have produced effects stupendous beyond all observed facts. But the hypothesis may be tested directly. A section across the zone of folding and faulting in Tennessee, from the French Broad river to White Rocks on Cumberland mountain, measures from the eastern outcrop of the Cambro-Silurian limestone to White Rocks 54 miles in a straight line and 72 miles on the dip-length of the limestone. The section includes four great faults, whose heaves are indefinite, but for this estimate are assumed at a minimum of from 1 to 3 miles; they may be twice as many miles. The unfaulted part of the section measures 28½ miles, dip-length 39 miles; the faulted part, on the assumed heave, 25½ miles, dip-length 33 miles. The apparent shortening is 18 miles in 72, or one-fourth. Claypole's result of a measurement across the zone of folding in Pennsylvania was a compression of 35 miles in 100, a reduction of one-third;[2] the dips in that district are usually steeper than in the faulted area and it is reasonable to consider the two measurements as accordant. Now, Reade gives us a formula for calculating the expansion of a zone when we know the depth of sediments; he finds an elongation of 2.75 feet per mile for a rise of temperature of 100° Fahr.; and a subsidence of 60 feet gives a rise of 1° Fahr. The strata deposited over this zone do not exceed 15,000 feet in thickness. From this fact we get a rise in temperature for their deepest layers of 250°Fahr. and an expansion of 6.9 feet per mile, or 373 feet for 54 miles. Reade would multiply this small amount by giving it the total value of the volumetric expansion of the rock mass and admitting only rise of the surface, as of water confined in a glass, but it does not appear that this vertical rise, were it ever so great, would supply the needed horizontal elongation. So we are forced to conclude that the rise of the isogeotherms is not alone a sufficient cause; yet it is a fact which must be given its appropriate place in any complete theory.

The other opponent of the contractional theory, who bases his own

[1] Origin of Mountain Ranges, T. Mellard Reade.

[2] British A. A. S., 1884, Montreal, p. 718. Pennsylvania before and after the elevation of the Appalachian mountains, E. W. Claypole.

hypothesis on the association of zones of folding with zones of great deposition, is Maj. C. E. Dutton. The objections which Dutton urges against the contractional theory are stated in his paper read before the Philosophical Society of Washington:[1]

The objection to this explanation is twofold: In the first place, we can not, without resorting to violent assumptions, find in this process a sufficient amount of either linear or volume contraction to account for the effects attributed to it. In the second place, the distortions of the strata are not of the kind which could be produced by such a process. As regards the first objection I will confine myself here to a mere reference to the very able analysis of the problem by Rev. Osmond Fisher. I see no satisfactory reply to his argument. As regards the second objection, which, if possible, is more cogent still, it may be remarked that the most striking features in the facts to be explained are the long, narrow tracts occupied by belts of plicated strata and the approximate parallelism of the axes of their folds. These call for the action of some great horizontal force thrusting in one direction. Take, for example, the Appalachian system, stretching from Maine to Georgia. Here is a great belt of parallel synclinals and anticlinals with a persistent trend, and no rational inquirer can doubt that they have been puckered up by some vast force acting horizontally in a northwest and southeast direction. Doubtless it is the most wonderful example of systematic plication in the world. But there are many others which indicate the operation of the same forces with the same broad characteristics.

The particular characteristic with which we are here concerned is that in each of these folded belts the horizontal force has acted wholly or almost wholly in one direction. But the forces which would arise from a collapsing crust would act in every direction equally. There would be no determinate direction. In short, the process could not form long, narrow belts of parallel folds.

With this forcible statement the hypothesis is dismissed as "quantitatively insufficient and qualitatively inadequate." The reputation of the writer and the vigor of his language have given this opinion great weight, and the contractional theory has been less favorably considered than before this attack. Nevertheless, I believe the opinion is not well founded and must yield to reconsideration.

The mathematical researches carried out by Rev. Osmond Fisher are summed up by him at the close of his book, and in regard to contraction he makes the following explanation of his method:

The well known fact *that great lateral compression has affected the stratified rocks of the earth's crust* is now generally explained by the supposition that the globe has contracted through secular cooling. It is thought that, as the cooling proceeded, the interior shrank away from the crust, and the latter became wrinkled, and that by this means the crumpling and contortions of the rocks were produced. We have accordingly calculated what the lateral pressure would be which would be available for crushing the strata of the earth's surface, supposing that the interior were to shrink away from the crust and to leave it unsupported. We find that it amounts to the enormous pressure of the weight of a column of rock of the surface density of the same section as the stratum and *2,000* miles long, or about 830,200 tons upon the square foot. We need not doubt that this pressure would be competent to perform the work expected of it.

Nor would any solid stratum in the interior of the earth be capable of sustaining the lateral pressure upon it, for these lateral pressures would be still greater within the earth than at the surface, except very near the center.

That the pressure thus produced would be abundantly sufficient for the purpose is,

[1]Dutton. Greater Problems of Physical Geography, p. 52. Bull. Phil. Soc. Washington, vol. XI, p. 52.

however, no proof that the work has been accomplished in that way. It has been an assumption often repeated, but never proved. The first task which we have proposed to ourselves is therefore to examine this point. We admit that the *inequalities of the earth's surface* have been caused by lateral compression, but we are not sure that this has arisen from secular cooling. We therefore commence our inquiry by seeking for some measure of the inequalities of the surface, as a preliminary step toward determining how they have been produced, *and in the first instance we include the greater inequalities, which constitute the oceanic and continental areas. But, although we have ocular proof that mountain chains have been formed by compression, it is mere matter of inference that the elevation of continents above the ocean floor is likewise due to the same cause.*[1]

The italics are mine and are intended to bring into opposition in the reader's mind two sets of unrelated facts which are included by the investigator in one inquiry. "Compression of stratified rocks" is a fact observed in certain narrow zones. The "greater inequalities which constitute the oceanic and continental areas" are features of the earth's surface of another order of magnitude, not causally related to zones of folding except as a necessary antecedent. Since compression has always occurred in an area of prior deposition, which requires land as a source of material and the sea as an agent, it follows that the "greater inequalities" in any given folded locality antedated folding; their cause holds no logical relation to the long subsequent effect. Neither has folding any necessary relation as cause to the continental uplift, which, following compression, raised the flexed and horizontal areas alike above sea. The Paleozoic continent and sea of North America had their origin in unknown causes of pre-Cambrian time. After Paleozoic deposition and deformation the rise of the whole continent lifted alike the Blue Ridge belt of crystallines, the folded zone of the Appalachian province, and the undisturbed strata of the Mississippi basin. The uplift bore no relation in area or time to the fact of compression, and it has gone on through geologic periods after folding ceased, as is shown by the ancient base levels, and revived drainage of the whole region east of the Mississippi valley.[2]

Fisher himself expresses a doubt on this point in the last sentence italicized, and Dutton, in the same article, in which he overthrows the contractional theory on Fisher's quantitatively insufficient result, asserts that the permanent changes of level of continents and oceans are due to a cause independent of isostasy.

Now it is sufficiently obvious that the theory of isostasy offers no explanation of these permanents changes of level. On the contrary, the very idea of isostasy means the conservation of profiles against lowering by denudation on the land and by deposition on the sea bottom, provided no other cause intervenes to change those levels. If, then, that theory be true, we must look for some independent principle of causation which can gradually and permanently change the profiles of the land and sea bottom. *And I hold this cause to be an independent one.* It has been much the habit for geologists to attempt to explain the progressive elevation of plateaus and mountain platforms, and also the foldings of the strata by one and the same proc-

[1] Physics of the Earth's Crust, by Osmond Fisher, p. 272.

[2] Rivers of Pennsylvania, W. M. Davis. Round about Ashville, B. Willis.

ess. I hold the two processes to be distinct and having no necessary relation to each other. There are plicated regions which are little or not at all elevated, and there are elevated regions which are not plicated. Plication may go on with little or no elevation in one geologic age and the same region may be elevated without much additional plication in a subsequent age. This is in a large measure true of the Sierra Nevada platform, which was intensely plicated during the Paleozoic and early Mesozoic, but which received its present altitude in the late Cenozoic.[1]

Gilbert and McGee[2] have also distinguished these phases of deformation and it seems unnecessary to argue further that Fisher has not discussed the theory of contraction as applied to the Appalachian province, since he is shown by his own assumptions and by the opinions of his eminent supporters to have confused the lesser problem of zonal compression with the far greater one of deformation of the spheroid. With that, Dutton's quantitative objection falls to the ground as at least not proved. It does not follow that contraction is quantitatively sufficient, but the question is still open.

His qualitative objection consists of two parts: (1) The force resulting from contraction would act equally in all directions—it would have no determinate direction; (2) it is necessary to assume a zone of weakness in the strata, simply because it is "required for the salvation of the hypothesis." It might be awkward for the supporters of the theory of contraction if the force could be shown to operate in some direction not across the compressed zone; but since it acts "in all directions" the properly directed force can not be denied its advocates. Its effects in other directions may probably be governed by mechanical conditions other than those that induce folding. And the reason for predominant action in a determinate direction is supplied by Dutton himself in the movement toward isostatic adjustment. Contraction gives to isostasy a needed force; isostasy directs contraction; the two effect a result which neither alone could bring about.

The reason for a zone of weakness in the accumulated strata was stated by Chamberlin in 1882:

The first effect of the attempt of the outer shell to settle down upon the interior would be to powerfully compress the beds. But when the limit of their compressibility under the existent conditions was reached further contraction could only be accomplished by the wrinkling of the layers themselves, whereby the greater portion of the crust was permitted to sink down with the contracting core, while certain belts were forced up into folds. The portion which would yield was not necessarily that which was thinnest and inherently weakest, but may have been that portion whose attitude placed it in a position unfavorable for resistance. For instance, if the strata had been previously bent downward by sedimentary accumulations upon them or bent upward by any preëxistent circumstance, such portions would be most liable to yield and relieve the strain, though they might perhaps be even thicker than other portions which remained unflexed because more favorably situated for resistance.[3]

This statement, of which I was not aware till August, 1890, when the hypothesis of initial dips and competent structure had been developed, anticipates my experimental studies. They only enforce Chamberlin's

[1] Bull. Phil. Society of Washington, vol. XII, p. 63.
[2] Gilbert, Lake Bonneville. McGee, Geol. Mag., Decade, III, 1888, p. 493.
[3] Geology of Wisconsin, vol. I, p. 75.

idea that the conditions which determine the place of folding are inherent in the attitudes of the material, not in the force. When a bent strut yields at the bend, the locating condition is in the strut, not in the thrust.

To every hypothesis brought forward to account for the folding of stratified rocks there is one objection made by its opponents: The cause is not quantitatively equal to the task required of it. For argument's sake, admitting for each and every one that the criticism is sound, I do not understand that it disposes of any which are based on good inferences from observed facts.

The process of deformation was exceedingly complex and thus afforded opportunity for the action of more than one cause. As the work performed was stupendous, it required the combined power of all available forces. We may well seek to assign an appropriate share to each of the causes proposed by the eminent scientists whom I have quoted, and I shall try to do so provisionally without now attempting to prove the various assumptions, which are necessary parts of such an essay.

It is essential to accept as an unexplained fact the existence of a continent throughout the Paleozoic age stretching away to the southeast from the present range of the Blue Ridge, and of a sea extending to the northwest 800 miles across to the Isle Wisconsin. Degradation progressed upon the continent and the resulting sands and muds were deposited in the sea, the bulk of them falling in a belt a few miles wide along the shore; organic life contributed to these deposits and their nature varied according to the character and amounts of mechanical and organic sediment. After lithifaction their rigidity differed according to their original composition and lamination, and in consequence of unequal deposits over adjacent areas the older strata had subsided unequally, producing initial dips and synclines of deposition. In the depths of these latter the temperature of the strata rose as they sank, and the consequent expansion resulted in the beginnings of more complex folding. The condition of isostasy prevailing in the earth's mass demanded that compensation should be made to the continental area for the load taken from it, and a deep seated flow was set up landward, a movement sufficient to restore elevation to the continent, which might otherwise have remained at rest. During the period of sedimentation, which ultimately set up isostatic adjustment, there had been continuous shrinkage of a nucleus cooling beneath the accumulating strata, and a corresponding compression strain existed in them without determinate direction or effect. Here were three continuous, growing conditions—sedimentation, isostatic adjustment, and contraction. There came a time when isostasy gave direction, and contraction gave the force to a movement of the submarine earth's crust toward the land, a movement extending seaward far beyond the zone of maximum sedimentary deposits, now folded, and including great extent of strata, now as then flat.

Begun at the southeast, where isostatic adjustment first gave to contraction effective direction, the movement spread indefinitely northwestward until the superficial flow from northwest to southeast included perhaps several degrees of arc of the earth's circumference. Let us pause a moment to grasp clearly what the rate and magnitude of this movement was. Originating in the slow growth of deep-seated isostatic adjustment and of contraction, the development must have been so gradual as scarcely to become effective in geologic ages, and yet the force was of an intensity so pronounced and involved masses so prodigious that it must have become simply irresistible. Whatever the resistance opposed to it, this pressure would gather until it was just greater; then, without violence, without shock, the opposed masses would yield.

Athwart this flow lay the shore zone of maximum sedimentary deposits; it must receive and yield to the force because it lay along the southeastern limit of isostatic adjustment against the relatively more resistant crystalline continent, and because the strata of this zone were already deflected from the direction of tangential thrust and therefore were weak in opposition to it.

Coextensive with the area of movement and the zone of initial flexure was the great Cambro-Silurian limestone, tougher, more massive, more continuous than any other stratum of the Paleozoic series. It transmitted the pressure, as none other could; it depressed synclines of deposition and competently raised all upward convex curves into anticlines. To its dominant influence in the mechanical reactions of the process is due the grand simplicity of the resulting structure; and the broad distinctions which divide the province into districts of folding or faulting may be traced to important stratigraphic conditions which influenced the effect of deformation of this most important member.

Two facts of dip have been dwelt on by all who have described Appalachian structure: the prevalence of southeastern dips and the steepness of northwestern dips. One result of unequal deposition was to produce a long shoreward, in the Appalachians southeastward, initial dip; and pressure from the northwest increased, but never overturned dips in the direction of its advance. Northwestern dips, on the contrary, whether original or subsequent, held the position of a limb revolved by opposing thrusts and were turned to verticality or overthrown.

If the hypothesis, which I have stated, be correct, Appalachian folding began at the time when deposition caused isostatic adjustment and adjustment localized and directed contraction. It paused when contraction was satisfied, and deposition then recommenced the process which ran its cycle again and again. Folding in this zone ceased altogether when epeirogenic deformation transferred the scene of deposition to another sea.

PLATE LXXV.

(Figs. *a* and *b* one-third of original size.)

Description of model:

Original length, 30 inches (not shown).

Width, 6 inches.

Thickness, 6¼ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	2	0	⅛	Very hard.
2	1	0	⅛	1⅛	Soft.
3	1	1	0	¼	Hard.
4	1	1	0	¼	Do.
5	1	1	0	⅜	Do.
6	1	1	0	¼	Do.
7	1	1	0	⅜	Do.
8	1	1	0	¼	Do.
9	1	1	0	⅜	Do.
10	1	1	0	¼	Do.
11	1	1	0	¼	Do.
12	1	0	⅛	1⅛	Soft.

The front face of the model was scored at intervals of 2 inches by saw cuts, which being filled with dark wax served as vertical datum planes to determine the adjustment of strata by slipping on bedding surfaces during bending.

Compressed under evenly distributed load of 500 pounds, equal to 2¾ pounds per square inch.

RESULTS.

Fig. *a*. Model is shortened 3 inches, or 10 per cent of original length, with formation of a rounded anticline next to the applied pressure. Hard layers are broken at the three points of sharpest curvature. Vertical datum planes show slipping on the bedding, which is confined to that section included in the fold.

Fig. *b*. Model is shortened altogether 9 inches, or 30 per cent of original length. The anticline has closed and the folded mass is thrust forward on a plane of fracture in the hard beds, making a fault, on a fault dip of 30°.

The position of the anticline at the end nearer the applied force was not in accordance with the hypothesis of bending under uniform load, which anticipated a central anticline.

(Fig. *a′* one-quarter original size.)

Description of model:

Original length, 30 inches (not shown).

Width, 6 inches.

Thickness, 3¼ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	0	⅜	Hard.
2 to 10 (inclusive).	1	1	0	10 x ⅛	Do.
11	1	1	⅛	1¼	Very soft.

Compressed 4 inches or 13·3 per cent under load of about 300 pounds, which was placed at the ends, leaving a small space in the middle without any load.

RESULTS.

A sharp broken anticline rose at the point where there was no load. Thus evenly distributed load did not control the position of the anticline, but extreme difference of loading did.

PLATE LXXVI.

(Illustration about 0·30 original size.)

Description of model:

Original length, 30 inches. Fig. *a*.

Width, 6 inches.

Thickness, 5 inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	2	0	½	Very hard.
2	1	0	½	1	Soft.
3 to 14 (inclusive).	1	1	0	12x$\frac{1}{16}$	Hard.
15	1	1	0	1	Do.
16	1	0	½	1	Soft.

The model was designed to show the nature of a fold in a series composed of a thick hard bed (15) underlying a number of thin beds. Under a uniformly distributed load of 500 pounds, equal to 2¾ pounds per square inch on the original length, it was compressed three times, as shown in Figs. *b* to *d*.

RESULTS.

Fig. *b*. The thick, hard stratum (15) formed an anticline 10 inches from the applied force and broke on the axis. The overlying thin, hard strata were carried up on this anticline and assumed a flat position between it and the load, with steep dips on either limb. The weight borne by the steeper limb of the anticline squeezed the soft layer (16), and this effect, combined with a scarcely noticeable initial dip in Fig. *a*, caused a second anticline to commence at 7½ inches from the resistance. The soft layers flowed into these arches.

Fig. *c*. The principal anticline is closed and the minor one is unchanged. The thick hard layer is much broken and is imbedded in the softer material.

Fig. *d*. The anticline is completely closed, and the model has been squeezed between the masses of shot which packed on each side of it.

Fig. *e* shows mammillated surface of model at the last stage, due to pressure transmitted through the mass of shot.

PLATE LXXVII.

(Illustrations one-third original size.)

Description of model:

Original length, $26\frac{1}{2}$ inches (not shown).

Width, 6 inches.

Thickness, $2\frac{7}{8}$ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1	1	1	0	$\frac{3}{8}$	Hard.
2 to 13 (inclusive).	1	1	0	12x $\frac{1}{8}$	Do.
14	1	0	$\frac{1}{3}$	1	Soft.

The model was designed to show the nature of a fold in a series composed of a thick hard bed over many thin hard beds; the difference of thickness assumed was moderate.

Under a uniformly distributed load of 500 pounds, equal to about 3·15 pounds per square inch on the original length, it was compressed five times, as shown in Figs. *a* to *e*.

RESULTS.

Fig. *a*. The hard strata (1 to 13 inclusive) forming a thick but weak series did not rise in a clearly competent anticline with this degree of shortening; but the soft layer (14) swelled and gave them an initial arch of flat crown, which exceeded the competent dip-length.

Fig. *b*. The pressure transmitted upward through the nearer limb of the initial arch raised it and formed a flat but competent anticline. The weight borne by the further limb of the anticline squeezed the soft layer (14) and gave rise to subsequent dips and the beginning of the consequent anticline. There is slight curvature of the strata near the resistance.

Fig. *c*. The first anticline is nearly closed in carinate form; the second has developed with a sharp crest and a small keel in the lowest hard layer (13), showing that it was competent, but was nearly filled by the flow of soft material from the region of increased weight to that of relief from load. The soft base has thickened near the resistance and has produced initial dips in the hard strata which arch over a small tunnel, showing the beginning of a competent anticline.

Figs. *d* and *e*. The folds previously determined are developed to closing without other deformation. The steeper dips throughout the whole series are toward the lower synclines and are directed both toward and away from the applied force.

PLATE LXXVIII.

(Illustration about 0·30 original size.)

Description of model:

Original length, 30 inches (not shown).

Width, 6 inches.

Thickness, 6¼ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	⅛	$\frac{3}{16}$	Very hard.
2	1	0	⅛	2	Soft.
3	1	1	¼	$\frac{3}{16}$	Hard.
4	1	1	¼	1¼	Do.
5	1	0	⅛	⅜	Soft.
6	1	1	¼	¼	Hard.
7	1	0	⅛	1½	Soft.

This model was designed to illustrate the effect of compression in a case where massive strata pass horizontally into thin bedded layers, as a limestone into a shale. To this end the gray layer (4) was so cast that at the left hand its apparently distinct bands formed a nearly solid mass, while at the right hand they were separated by oiled surfaces. In so casting this layer a line of weakness was developed across the center of the layer (4) where the anticline was afterward formed.

Under a uniformly distributed load of about 800 pounds, equal to nearly 4 pounds per square inch on the original length, the model was compressed once from 30 inches to 27½ inches. The pressure box then broke down. The pressure was applied from the right against the weak end of No. 4.

RESULTS.

The weakness of layer No. 4, the softness of most of the material, and the relatively great thickness of the model caused first general thickening according to the softness of the layers and then the rise of an anticline where No. 4 was weakest.

No. 4 yielded unequally; the massive left-hand end formed a gentle curve with the other strata; the thin bedded right-hand end assumed several folds peculiar to itself. Within the principal anticline, beneath the upper half of No. 4, there was a region relieved of load, into which the lower layers of No. 4 were thrust with production of faults on each side of the anticline. A structure similar to this has been recognized near Newmansville, Tenn., where Cambrian strata form an anticline over Silurian (Greenville sheet, Tennessee, by Arthur Keith).

The other strata show adjustment to load and space by thinning and thickening.

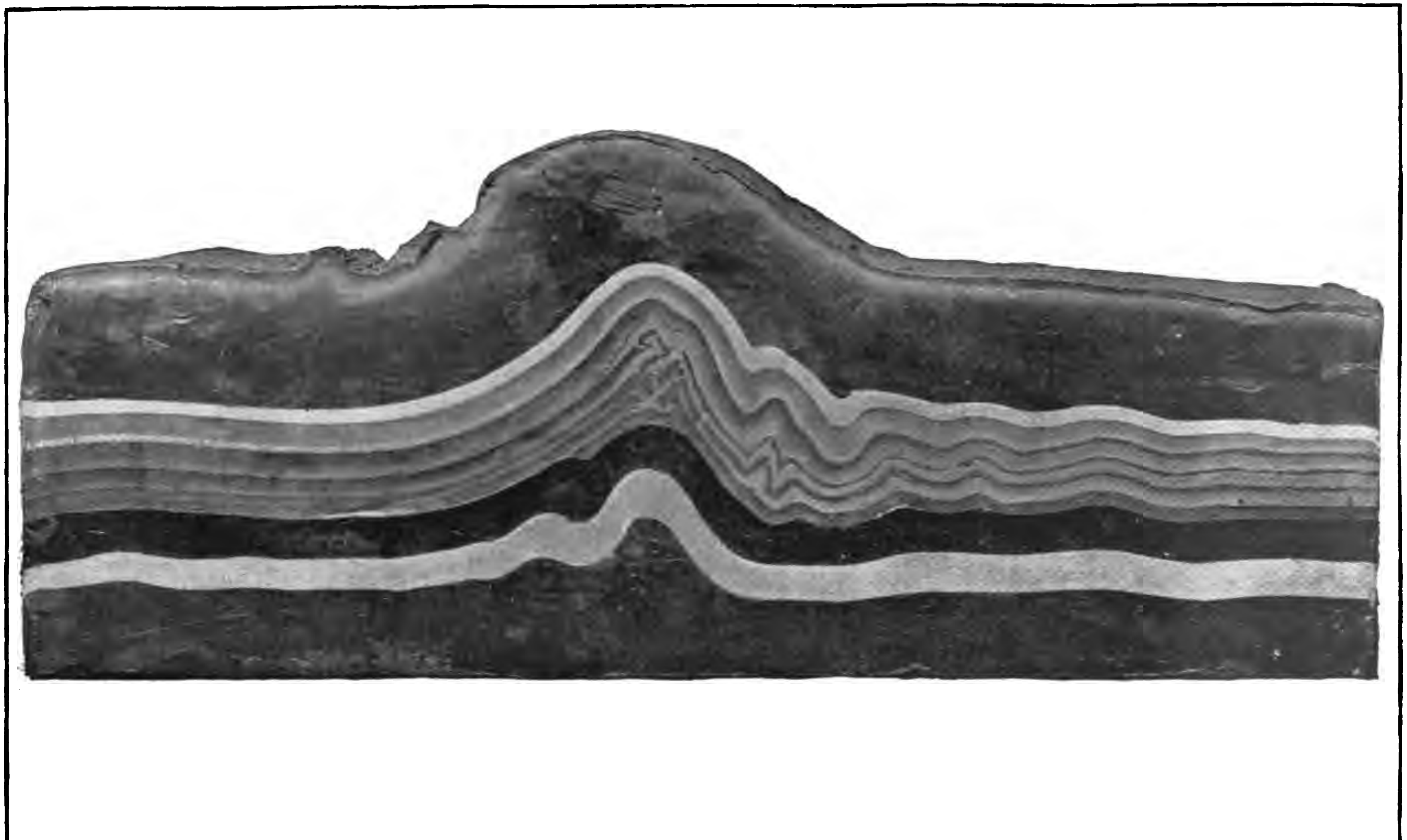


PLATE LXXIX.

(Illustration 0·223 original size.)

Many preceding experiments indicated that initial or consequent dips in the models determined the positions of anticlines. Therefore the models marked A to G. 1, Plates LXXIX to LXXXVI, were constructed to test the control exercised by dip.

Description of Model A:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 3½ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V turpentine.	*Inches.*	
1	1	1	0	⅛	Hard.
2 to 13 (inclusive).	1	1	0	12x⅛	Do.
14	1	0	½	2¼	Soft.

The soft base was cut to the form shown in Fig. *a*, and the hard layers were placed upon it under a load of 1,100 pounds and allowed to stand two hours. They then comformed to the initial dips required by the base, Fig. *a*, with the marked change in dip 6 inches from the applied force.

Under uniformily distributed load of 1,100 pounds, equal to about 5½ pounds per square inch of original length, the model was compressed four times, as shown in Figs. *b* to *e*.

RESULTS.

An anticline was formed with the acute crest of the arch coincident with the upper line of initial dip. The anticline was competent, as shown by the tunnel within it, and continued compression closed it, forming a carinate fold, Figs. *b*, *c*, *d*, and *e*.

Description of Model C, Figs. *a′* and *b′*:

This model was constructed of the same materials and after the same manner as the preceding, but with the line of the initial dip at 18 inches, or three times the distance from the applied force.

It was compressed once, under load like the preceding.

RESULTS.

An anticline, similar in form to that obtained in Model A, rose at the line of assumed dip.

PLATE LXXX.

(Illustration 0·22 of original size.)

Description of Model B:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3¼ inches.

Layers.	Compositon. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	⅛	⅛	Firm, but brittle.
2 to 13 (inclusive).	1	1	⅛	12 x ⅛	Do.
14	1	0	⅛	2⅛	Soft.

This model was of the same form and make-up as Model A, Plate LXXIX, but of softer materials.

It was compressed six times, under uniform load of 1,100 pounds, after the same manner as A. An anticline was determined in position by the initial dip and developed with a keel within and a small overthrust toward the applied force. The external form of the anticline was rounded since the firm but flexible strata conformed to a curve without fracture.

PLATE LXXXI.

(Illustration about two-ninths original size.)

Description of Model D:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 3½ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1	1	1	⅛	½	Firm, but not brittle.
2 to 13 (inclusive).	1	1	⅛	12 x ⅛	Do.
14	1	0	½	2½	Soft.

This model was of the the same make-up as model C, *a′* and *b′*, Plate LXXIX, but of softer materials, like those used in B. The initial dip was at 24 inches from the applied force.

Under uniformly distributed load of 1,100 pounds it was compressed six times, Figs. *b* to *g*, inclusive. The negatives of the stages *d* and *e* were lost, and the illustrations of these two stages are restorations by the writer from memory and measurement. Figs. *g′* and *g″* are different views of the model at the stage *g*.

RESULTS.

The softer character of the materials and the remoteness of the initial dip, as compared with that in B, Plate LXXX, resulted in thickening of the strata and slight increase of the dips in the stages *b* and *c*. The influence of the initial dip determined an anticline at the line 21½ inches from the applied force in *c*, and this developed as a competent carinate fold with a slight overthrust, but the consequent dips induced by the unequal thickening of the soft base caused the growth of two consequent folds of approximately equal dip-lengths.

PLATE LXXXII.

(Illustration 0·222 original size.)

Description of Model D 11:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3½ inches.

Layers.	Composition. (Parts by weight.)*			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	....	....	....	½	Firm, but not brittle.
2 to 13 (inclusive).	....	....	....	12 x ⅛	Do.
14	....	....	....	2½	Soft, but stiff.

* The layers of this model were recast from those of the model D, Plate LXXXI, with the intention of reproducing that experiment. The model D had stood for a month exposed to the air, and the soft base had changed by evaporation and in process of remelting.

The conditions of this experiment were identical with those of the experiment D, except that the materials had become a little stiffer. In this case, as in D, the original anticline was determined by the initial dip; but in place of two consequent folds determined in D by the soft base, there arose in this case a single anticline, due to the immediate thickening of the stiff base next to the applied force.

PLATE LXXXIII.

(Illustrations 0·22 original size.)

Description of model E:

Original length, $39\frac{3}{8}$ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, $1\frac{3}{4}$ to $2\frac{3}{4}$ inches.

Layers.	Composition. (Parts by weight.) Wax.	Plaster.	V. turpentine.	Thickness.	Character.
				Inches.	
1	1	1	0	$\frac{1}{4}$	Hard.
2 to 9 (inclusive).	1	1	0	$8 \times \frac{1}{16}$	Do.
10	1	0	$\frac{1}{8}$	1 to 2	Soft.

The composition of this model was like that of A, Plate LXXIX, and the arrangement was similar; but the hard layers were only half as thick, and the soft base was an inch thicker at one end than at the other; this does not appear in Fig. *a*, as the photograph was not properly trimmed along the base.

Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

The initial dip near the applied force controlled the position of folding, and there developed a carinate anticline which grew higher and higher until it had taken up all of that section of the model between its axis and the applied force. In the stage shown in Fig. *d*, the weight on the further limb of this anticline squeezed the soft base and gave rise to dips which determined a consequent anticline. In the stage shown in Fig. *h* a similar condition arose, producing a second consequent anticline. All of these folds were forced into one complex structure.

At the end next to the resistance there was some deformation with each compression, but it was so moderate in amount as to show that nearly all the applied force was absorbed in raising the nearer anticlines with their load.

PLATE LXXXIV.

(Illustrations 0·22 original size.)

Description of Model E 1:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 1¾ to 2¾ inches.

Layers.	Composition (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1	1	1	0	¼	Hard.
2 to 9 (inclusive).	1	1	0	8 x 1/16	Do..
10	1	0	⅛	1 to 2	Soft.

This model was made exactly like E, Fig. *a*, Plate LXXXIII, but the pressure was applied at the thinner end, remote from the principal assumed initial dip. A very slight initial dip limited the syncline on the right. Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

Deformation went on during each compression at three places: at the applied force, at the minor initial dip, and at the sharper initial dip. In Fig. *b* the anticline at the sharper dip, furthest from the applied force, is just entering on the competent stage of development, and its growth from that on is continuous with the formation of an overthrust of typical Appalachian character. But the minor initial dip, exaggerated in Fig. *b*, has developed to a carinate anticlinal in Fig. *c;* at the next stage it is overthrust, and in Figs. *e* and *f* two consequent folds appear, one on each side of the original. These are caused by the resistance offered against the overthrust and by the weight which it must raise in developing. In Fig. *c* there is a broad swelling of the plastic base near the applied force, which caused a flat anticline that never rose above the inflowing soft material.

The relations of the two original anticlines in Fig. *d* are characteristic of the structure of northeastern Alabama.

PLATE LXXXV.

(Illustration 0·22 of original size.)

Description of Model G:

Original length, 39⅜ inches = 1 meter. Fig. *a*.

Width, 5 inches.

Thickness, 2½ to 3¼ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 to 19 (inclusive).	1	1	½	1⅛	Soft, but firm.
20	1	0	1	1 to 2	Very soft.

This model was arranged in the same manner as Model E, Plate LXXXIII, but all of the materials were much softer. An intermediate set, lettered F, is not illustrated in this article.

Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

The principal initial dip near the applied force was influential in producing a rounded anticline, which grew until it had absorbed the entire section between its axis and the force. Consequent anticlines developed in succession, as appears in Figs. *d* and *f*, and the minor initial dip having been exaggerated slightly in the stage shown in Fig. *h*, determined the development of a small close anticline when the model was so shortened that the soft layers transmitted the pressure to it. The recurved form of the principal anticline toward the applied force is due to the fact that the piston was lower than the top of the fold and pushed in the base.

PLATE LXXXVI.

(Illustration 0·22 of original size.)

Description of Model G 1:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 2½ to 3½ inches.

Lawyers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 to 19 (inclusive).	1	1	⅓	1½	Soft, but firm.
20	1	0	1	1 to 2	Very soft.

This model resembles the preceding one in its arrangement and composition, and is like E 1, Plate LXXXIV, in its form and the manner of application of the force.

Under a uniform load of 1,100 pounds the model was compressed eight times, as shown in Figs. *b* to *i*.

RESULTS.

In the first two figures, *b* and *c*, the model shows no deformation due to folding, but only a slight thickening of the soft base near the applied force and the beginning of a fold on the further side at the center of the syncline. In Fig. *d* the thickening of the soft base has folded up into a flat anticline, and a second thickening has developed in a consequent manner at some distance in advance of this fold. The subsequent stages show the continued development of the two anticlines consequent upon the thickening of the soft base, and of the small fold in the syncline. At the stage shown in Fig. *h*, the sharp initial dip furthest from the applied force determined a very small anticline, which showed some further development in Fig. *i*.

When this model is compared with E 1, Plate LXXIV, it is seen that the plastic character of the base and of the overlying layers in this case prevented the transmission of the force to the initial dip, which in Model E 1 was influential in producing a much more pronounced anticline remote from the force. This influence of the plasticity of layers would enter into the results of pressure transmitted through strata at greater or less depths in the earth's crust, and the models would indicate that the firmer the strata the greater the distance to which they would transmit pressure.

PLATE LXXXVII.

(Illustration 0·22 of original size.)

Description of Model H:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 2½ to 3½ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1 to 12 (inclusive).	1	1	⅜	12 x $\frac{1}{16}$	Soft.
13	1	1	½	½	Do.
14 to 17 (inclusive).	1	1	⅜	4 x $\frac{1}{16}$	Do.
18	1	0	1½	1 to 2	Very soft.

This model in all respects resembled G 1, Plate LXXXVI, except that the base was still softer than in that case.

Under uniform load of 1,100 pounds it was compressed seven times, in order to test the nature of the consequent development of strata, which it was supposed would be more likely to predominate upon the softer base.

RESULTS.

In Fig. *b* there is a thickening of the base and the initial development of two consequent folds. These folds continued to develop with minor contortion, and the second from the applied force became an important carinate anticline with a detached anticlinal core, involving minor folds upon its limbs. The initial dip remote from the force was slowly accented from stage to stage of compression, but did not at any time develop a fold, even so small as that in a similar position in G 1.

PLATE LXXXVIII.

(Illustration 0·22 of original size.)

Description of Model H 2:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 1¾ to 3¼ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 and 2	1	1	⅛	2 x $\frac{1}{16}$	Soft.
3	1	1	⅛	⅜	Do.
4 to 7	1	1	⅛	4 x $\frac{1}{16}$	Do.
8	1	0	1⅛	0 to 1¾	Very soft.
9	1	1	⅛	$\frac{1}{16}$	Soft.

This model was designed with the intention of removing the influence due to pressure against the soft base and consequent swelling in advance of the piston. The bottom layer was introduced because the thick layer which would otherwise form the base was so soft that the model could not be handled.

Under a uniform load of 1,100 pounds the model was compressed six times, as shown in Figs. *b* to *g*. In Fig. *b* the initial synclinal form is exaggerated, and in Fig. *c* the tendency to depression in the syncline nearest the applied force, which was resisted by the firm base of the box, was deflected upward, causing an anticline upon the slope toward the force. This anticline in turn caused a second fold in advance of it, which became the predominant feature of deformation.

PLATE LXXXIX.

(Illustration 0·22 of original size.)

In the preceding models, from A, Plate LXXIX, to H II, Plate LXXXVIII, the strata above the plastic base have had the form of a very gentle initial syncline, as shown in each case in Fig. *a*. It was supposed that such a syncline might develop in actual strata in consequence of the deposition of unequal thicknesses, and that the occurrence of greater thickness over the synclinal area might be influential in affecting the character of the folds. In order to test this idea several models were constructed, and pressure was applied to the synclines from different ends.

Description of model FH:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 3½ to 4½ inches, with syncline of deposition arranged with its axis at 27 inches from the applied force.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 to 8	*1	*1	*⅜	1 to 2	Soft but firm.
9	1	1	⅜	⅛	Do.
10 to 15 (inclusive)	1	1	⅜	⅛	Do.
16	1	0	3	1 to 2½	Very soft.

* Including the thickness of the syncline.

Under a uniform load of 1,100 pounds this model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

The original syncline was preserved throughout until the pressure of the piston below the crest of the consequent anticlines pushed in a wedge of folded strata which exaggerated the dip from the applied force. The thickening of the very soft base, in this as in other similar cases, produced two consequent folds near the applied force, the further one of which became the more important and developed into a carinate anticline.

PLATE XC.

(Illustration 0·22 of original size.)

Description of Model K:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3¼ inches.

Preliminary pile, full thickness shown at left end.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1 white, 3 black, 4 white, 5 black, 6 white	1	1	1	¾	Soft, but firm.
7 to 12, 13 black	1	1	2	¼	Very soft.
14 white, 15 to 19, 20 white	1	1	3	1½	Soft as butter at 70° F.

This pile having been made it was cut away on the bottom by a very small amount each time, as many times as there are layers at the right end above the thick white one (1); the cutting was unequal, and gave the bottom at each shaving an uneven surface. After each shaving the model was turned upon its bottom and pressed down on a flat surface, producing in the top a gentle syncline in which a thin layer could be cast. When this was cooled the bottom was shaved again, the model was again pressed on a flat surface, and a second thin layer cast in the new depression. Thus after many shavings and castings the thick white layer (1) was depressed at the right-hand end like a stratum sunk beneath a mass of conformable deposits of unequal thickness, and it extended diagonally through the model with variable initial dips. At the right hand end the casting consisted of:

Layers	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1 to 19, 20—heavier black	1	1	1	1¾	Soft, but firm.
21 to 42	1	1	3	1½	Soft as butter at 70° F.
1 of left end white	1	1	1	½	Soft, but firm.

Under a uniform load of 1,100 pounds the model was compressed nine times, as shown in Figs. *b* to *k*.

RESULTS.

(This represents pressure applied to thick strata in a syncline of deposition.) The initial dips in the principal diagonal layer, extending from the base at the right to the top at the left, controlled the important features of deformation. In Fig. *c* a single competent anticline rose at the nearer initial convex curve, and in Fig. *i* the further curve of the same character caused a remote anticline. A small consequent anticline, begun in Fig. *g*, lies between these two. The nature of minor deformation was determined by the plasticity of the materials. The soft but firm layers (1 to 20) folded in little anticlines and synclines. The butter-like material folded and also sheared on small fault planes, the first of which is seen in Fig. *b* to the right of the middle, and others in Fig. *k* beneath the consequent and second original anticlines. The softest material was squeezed from the limbs into the axial regions of the folds.

PLATE XCI.

(Illustrations 0·22 of original size.)

Description of Model L:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3½ inches.

Preliminary pile, full thickness shown at right end.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 white				¾	
3 black, 4 white, 5 black, 6 white	1	1	1	¾	Soft but firm.
7 to 12, 13 black	1	1	2	¾	Very soft.
14 white, 15 to 19, 20 white	1	1	3	1¼	Soft as butter at 70° F.

Like the preceding one, this model was alternately shaved on the bottom, pressed down flat, and filled in on top with new layers until it had the form shown in Fig. *a*. The section at the left end then consisted of:

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.		
				Inches.	
1 to 4	1	1	1	1	Soft but firm.
5 to 13	1	1	3	2	Soft as butter at 70° F.
1. of the other end, black.	1	1	1	½	Soft but firm.

Under a uniform load of 1,100 pounds this model was compressed eight times, as shown in Figs. *b* to *l*.

RESULTS.

(This represents pressure applied to strata beneath the thin edge of a mass in a syncline of deposition.) The very slight initial dip in the heavy black layer near the applied force produced an anticline which was succeeded by a consequent fold. These two, with minor folds and shear thrusts, constitute the entire deformation. The principal initial dip in the competent black layer, remote from the applied force, was not affected by compression, because the soft materials yielded immediately.

PLATE XCII.

(Illustration 0·217 original size.)

Description of Model M:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 5½ inches.

Preliminary pile, full thickness shown at both ends.

Layers.	Composition. (Parts by weight.) Wax.	Plaster.	V. turpentine.	Thickness.	Character.
				Inches.	
1 black	1	1	⅓	1	Relatively hard but flexible.
2 white	1	1	3	¼	Soft as butter at 70° F.
3 black				1	
4 white				¼	
5 gray				1½	

This pile was shaved unevenly on the bottom, pressed down flat, and filled in until a syncline was formed, Fig. *a*. Then additional layers were cast conformably over the whole length. The material with which the syncline was filled was of the softest character (wax, 1; plaster, 1; V. turpentine, 3). The overlying layers were of varied but firmer composition.

Layers.	Model.	Composition. (Parts by weight.) Wax.	Plaster.	V. turpentine.	Thickness.	Character.
					Inches.	
1 to 2	(E)	1	1	0	2x¼	Hardest, frangible.
3 to 4	(G)	1	1	⅓	2x⅛	Hard but flexible.
5	(E)	1	1	0	¼	Hardest, frangible.
6	(F)	1	1	⅔	¼	Hard.
7 to 8	(G)	1	1	⅓	2x⅛	Hard but flexible.
9	(F)	1	1	⅔	¼	Hard.
10	(E)	1	1	0	¼	Hardest, frangible.

Under a uniform load of 1,100 pounds the model was compressed ten times, as shown in Figs. *b* to *l*.

RESULTS.

This model consisted essentially of the massive, competent layer (1) of the preliminary pile, dipping beneath a syncline of deposition and of an overlying competent series of alternating hard and very hard layers. These two competent members acted independently to a certain degree. In the massive layer the initial dip determined the principal anticline of the lower series, which became overturned from the applied force in the stage shown in Fig. *i*. The absence of dips in the upper series gave immediate effect to the applied force and produced a double anticline near the end. The competent nature of these smaller folds is shown in the axial thickening of the less hard layers. The soft material filling the syncline served to allow independent movements of the two competent members, and was itself deformed by local pressures and relief from load. The overturn in the lower competent member was determined by the fact that one syncline was deeper than the other and the anticline was free to move in the superincumbent soft mass.

PLATE XCIII.

(Illustrations 0·22 of the original size.)

Description of Model J:

Original length, 39⅜ inches = 1 metre. Fig. *a*.
Width, 5 inches.
Thickness, 3¼ inches.

Layers.	Composition. (Parts by weight.)			Thickness.	Character.
	Wax.	Plaster.	V. turpentine.	*Inches.*	
1 to 4 white and black	1	1	1	4x⅛	Soft but firm and flexible.
5 white	1	1	1	⅛	
6 to 8 black and white	1	1	2	3x⅛	Softer.
9 yellow	1	1	2	⅛	
10 and 11 black and white	1	1	2	2x⅛	
12 black	1	1	2	¼	
13 green	1	1	3	⅛	Softest. This material was like butter at 70° F.
14 black	1	1	3	⅛	
15 red	1	1	3	⅛	
16 black	1	1	3	⅛	
17 and 18 white and black	1	1	3	2x¼	
19 purple	1	1	3	⅛	

This model was constructed to ascertain the nature of deformation in materials of plastic character confined beneath those of firm and flexible nature. The model was compressed under uniformly distributed load of 1,100 pounds nine times. Figs. *b* to *k*.

RESULTS.

As no initial dips were assumed the position of deformation was determined by swelling near the applied force. In the stage represented in Fig. *c* the arch of the upper strata is about entering on development as a competent structure, and the lowest strata are rising into the hollow of the arch by a fault, whose beginning is apparent in the little point of white of layer 17 at its greatest rise. In Fig. *d* this fault is seen clearly developed, with clean cut edges, and it is confined to the softest, butter-like material, which is relieved of pressure by the overarching competent layers.

As the competent anticline continued to rise the mass of softest material was compelled to change form without change of volume; it was shortened and given space for added height. To this change it accommodated itself by faulting, that is by flowing on definite planes, not by general flow within the whole mass; the fault planes divided the mass at first into rhombs, bounded by two faults and two bedding planes, and afterwards into triangular forms, bounded by two faults and one bedding plane. The triangular prisms were so related that the verticle movement in each pair was in opposite directions and the change of form was accomplished as by two wedges moving one against the other. This appears most clearly in Figs. *f*, *g*, and *h*. This faulting may be called incompetent structure in distinction to the growth of the anticline, which is competent structure.

The rise of the competent anticline continued until it overtopped the piston by which pressure was applied. Then the nearer limb of the fold was pushed under the further limb and the strata in the inversion were stretched, producing an overthrust of the alpine type described by Heim—a stretch thrust.

PLATE XCIV.

(Illustrations one-half original size.)

Model J:

This plate presents three views of the model shown in all its stages in Plate XCIII. These views are from the other side opposite those of the complete series and correspond:

Fig. *a* of this plate to Fig. *g*, Plate XCIV.
Fig. *b* of this plate to Fig. *h*, Plate XCIV.
Fig. *c* of this plate to Fig. *k*, Plate XCIV.

PLATE XCV.

(Illustrations 0·22 of the original size.)

Description of Model J 1:

Original length, 39⅜ inches = 1 metre. Fig. *a*.

Width, 5 inches.

Thickness, 3¼ inches.

This model was made up of layers which varied in thickness precisely as did those in model J, Plate XCIII; but in this case all the layers were of one consistency, of the softest material that could be handled, composed of wax 1, plaster 1, V. turpentine 3 parts. This substance resembled butter at 70° F.

The model was compressed under uniformly distributed load of 1,100 pounds, seven times, as shown in Figs. *b* to *h*. The four figures below *h* represent the opposite side of the stages indicated by the letters.

RESULTS.

The material being homogeneous and very soft no layer or series of layers, nor even the whole model, was competent to form an arch which would support the load. Therefore the structures developed were incompetent. The first deformation was by shortening and rising near the applied force, and the adjustment of volume to modified form was by rise of the sections on both sides of a wedge-shaped prism—Figs. *b* and *c*. This deformation produced initial dips, which (to an extent limited by the weakness of the strata) caused the resolution of the pressure into components tangential and radial to the curves. The radial components continuously exaggerated the curvature and new initial dips arose, which had a similar effect. Thus folding ensued, but without competent character. There are no carinate anticlines and the strata are not materially thickened or thinned, except in the case of the lower white layer in Fig. *e* and those which follow; the thickening there indicates a tendency toward competent development of arches of narrow span.

The model was characterized by striking differences of structure on opposite sides; on the one side the dominant feature is folding, with minor faults; on the other side thrusting developed successively from small folds in a manner very much like Cadell's results in hard materials. It is possible that if the substance had been a little firmer only folding would have developed, and if the substance had been softer deformation would have proceeded by thrusting only.

PLATE XCVI.

(Illustrations one-half original size.)

Model J 1:

This plate presents two views of the model shown in all its stages in Plate XCV. They represent the model at the stage marked *f*, and show the differences of deformation on the two sides.